CONTRACT NO. NAS8-37137

# VOLUME II
# APPENDIX 1
# TRADES STUDIES

(NASA-CR-183601) LIQUID ROCKET BOOSTER STUDY. VOLUME 2, BOOK 2, APPENDIX 1: TRADES STUDIES Final Report, Nov. 1987 - Feb. 1988 (General Dynamics Corp.) 374 p CSCL 21H

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# LIQUID ROCKET BOOSTER STUDY
## FINAL REPORT

GENERAL DYNAMICS
*Space Systems Division*

CN24L ( 0) ( 2)
TURNER J/PUBLICATION
MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE AL.

RETURN ADDRESS CN22D

GDSS-LRB-MEM-88-01

# INITIAL TRADE STUDIES
# ON
# LIQUID ROCKET BOOSTERS
# FOR THE STS SYSTEM

Under Contract NAS8-37137, during the time period November 1987 through February 1988, the following major trade studies were performed with formal direction by the GDSS Engineering Review Board.

Some conclusions have subsequently changed, as noted in the "updates". They are provided as background information.

GENERAL DYNAMICS
SPACE SYSTEMS DIVISION

Under DR-10, "Configuration Evaluation and Criteria Plan", fifteen level one trades were planned. Figure 1 lists these trades plus a sixteenth on separation.

Attached are the results of this work which was completed in February 1988. Note that:

1.4 "Degree of Recovery/Reuse" was combined with 1.13 "Recovery System Selection".

1.11 "Flight Control Implementation" is not included because it is really an analysis, not a trade, involving the use of a six degree of freedom flight simulation model to analyze required gimbal angles and rates.

Since they were so closely related, trades 1.7 (Chamber Pressure), 1.12 (Tank Config.) and 1.14 (Pressurization System) are grouped together.

These trades all used the same selection criteria, emphasizing safety and reliability as shown in Figure 2. Much of this data fed into vehicle concept selection which was made based on the same criteria. One of the indirect advantages of the formal trade/ERB review process was to include the whole study team in discussions of LRB requirements, constraints, assumptions and selection criteria.

# LRB TRADE STUDY ASSIGNMENTS AND STATUS

| PAGE | TRADE STUDY | LEADER | SYSTEMS | STATUS |
|---|---|---|---|---|
| 8 | 1.1 CONFIGURATION OPTIMIZATION | D. SMITH | G.FARMER | FINAL 7 DEC 87<br>WRITING REPORT |
| 26 | 1.2 NO OF ENGINES & ENGINE OUT | G. MEHTA | G. FARMER | FINAL 7 DEC 87<br>WRITING REPORT |
| 52 | 1.3 ABORT MODE OPTIMIZATION | J. PATTON | G. FARMER | INITIAL 12 NOV 87<br>INTERIM 7 DEC 87<br>INTERIM 14 JAN 88 |
| 86 | 1.5 PUMP FED - PROPEL SELECTION | T. NGUYEN | M. VACCARO | FINAL 4 DEC 87<br>WRITING REPORT |
| 104 | 1.6 PRESS FED - PROPEL SELECTION | T. NGUYEN | M. VACCARO | FINAL 4 DEC 87<br>WRITING REPORT |
| 114 | 1.7 PRESS FED - CHAMBER PRESSURE SELECTION | W. PIERCE | M. VACCARO | INITIAL 5 NOV 87<br>FINAL 12 JAN 88<br>WRITING REPORT |
| 160 | 1.8 PUMP FED - ENGINE PERFORM/SELECTION | G. MEHTA | L. PENA | INITIAL 8 DEC 87 |
| 178 | 1.9 PRESS FED - ENGINE PERFORM/SELECTION | G. MEHTA | L. PENA | INITIAL 8 DEC 87 |
| 200 | 1.10 PROPULSION - IGNITION SEQ AND HOLD DOWN | J. DAVIS | L. PENA | INITIAL 17 NOV 87 |
| 120 | 1.12 TANK CONFIGURATION SELECTION | T. SACZALSKI | L. PENA | INITIAL 11 DEC 87<br>INTERIM 15 JAN 88 |
| 232 | 1.13 RECOVERY SYSTEM SELECTION | A. ORILLION | G. FARMER | (REVIEW VIA PHONE)<br>INITIAL 15 JAN 88 |
| 146 | 1.14 PRESS FED - PRESS SYSTEM SELECTION | W. PIERCE | M. VACCARO | INITIAL 1 DEC 87 |
| 270 | 1.15 FACILITY OPTIMIZATION | J. WASHBURN | L. PENA | INITIAL 5 NOV 87 |
| 290 | 1.16 SEPARATION SYSTEM SELECTION | P. BRENNAN | L. PENA | COMPLETED |
| 349 | 1.17 LRB STIFFNESS | V. SHEKHER | | COMPLETED |

LIQUID ROCKET BOOSTER
Trade Studies

Listing and Descriptions

| TS # | Trade Study Title | Trade Study Description |
|---|---|---|
| 1.1 | Length - Diameter Optimization | Determine the optimum length to diameter ratio (L/D) and configuration of the LRBs to achieve required performance and maintain acceptable aerodynamic loads on the Orbiter wings. |
| 1.2 | Number of Engines & Engine Out Trade | Perform an analysis of Orbiter and LRB engine-out capability resulting in a definition of required LRB total impulse (and thrust level). Selection of the appropriate sized engine (and the number of engines required) are based on thrust requirements. |
| 1.3 | Abort Mode Optimization | Determine improved STS abort modes and scenarios which can be implemented with the use of LRBs. Provide recommend abort modes for all ascent flight phases. Abort modes should offer greater mission flexibility and/or reduced (STS) LCC. |
| 1.4 | Degree of Recovery/ Reusability | Selection of no recovery, P/A module recovery, and/or tank recovery modes. Determine the degree of reusability and refurbishment of recovered equipment. |
| 1.5 | Propellant Selection | Select propellants based on performance, safety, and LRB configuration constraints (L/D) for a pump fed propellant system. Present alternatives are: LO2/LH2, LO2/CH4,LO2/C3H8, LO2/RP-1, LO2/CH4/LH2, LO2/C3H8/LH2, LO2/RP-1/LH2, N2O4/A-50,N2O4/MMH. |
| 1.6 | Propellant Selection | Selection of propellants based on performance, safety, and LRB configuration constraints (L/D) for a pressure fed propellant system. Present alternatives are: (see T.S. 1.4) |

| TS # | Trade Study Title | Trade Study Description |
|---|---|---|
| 1.7 | Chamber Pressure Selection | Selection of the optimum tank and chamber pressures to obtain minimum engine, tank and propellant weight for a pressure fed LRB propulsion system. |
| 1.8 | Engine Performance/ Selection | Selection of the appropriate pump fed engine based on propellant selection and thrust (also dependent on number of engines) requirements. |
| 1.9 | Engine Performance/ Selection | Selection of the appropriate pressure fed engine based on propellant selection and thrust (also dependent on number of engines) requirements. |
| 1.10 | Ignition Sequence and Hold Down | Investigate ignition sequence, thrust build-up, and release characteristics to minimize the "twang" prior to lift-off. |
| 1.11 | Flight Control Implementation | Selection of source of flight control. The sources are LRB (autonomous control), Orbiter GPCs (as SRMs), or a combination. |
| 1.12 | Tank Configuration Selection | Selection of the recommended tank config. & materials including consideration of insulation and thermal protection. Both Pump and pressure fed systems will be investigated and a recommendation will be provided for each type of propellant system. |
| 1.13 | Recovery Systems Selection | Selection of the recommended LRB recovery systems including consideration of separation, trajectory, thermal protection, deployment, control, landing impact attenuation, landing sites, and reusability / refurbishment. |
| 1.14 | Pressurization System Selection | Select method and systems for pressure fed propulsion system's tank pressurization. |
| 1.15 | Facility Optimization | Determine the best launch/MCS concepts to be used to process and launch the Liquid Rocket Booster while minimizing interface impacts with the STS. |

# PRIMARY SELECTION CRITERIA

We have defined selection criteria we believe reflect the principal thrust of the LRB systems study. Although no weighting factor is associated with a given criterion, safety, reliability, STS compatibiltiy, and performance are viewed as primary. These are basically go / no -go screening criteria. The remaining criteria, including cost, are viewed as secondary. Although important, secondary criteria may not be used to select a candidate LRB concept that does not sufficiently satisfy the primary criteria.

Each trade study and the concept selection process used these same criteria. For example, we have not necessarily selected the lightest or highest performance system or concept, but rather aimed for the safest and most reliable. Foremost in our mind was the fact that LRB must integrate into the manned STS and improved safety and reliability.

Traditional methods of applying a numerical score and weighting factor to a subjective criterion do not provide the necessary insight into why one LRB concept faired better than another. The rationale must be clearly stated in written form; this will allow NASA to evaluate the thought process by which the evaluation was made, and will serve as an important step in evaluating and selection process documentation.

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# PRIMARY CRITERIA MATRIX

LRB

| SELECTION CRITERION | SELECTION CRITERION DEFINITION | SELECTION CRITERION ELEMENTS |
|---|---|---|
| SAFETY / ENVIRONMENTAL ACCEPTABILITY | EXTENT TO WHICH LRB CONCEPT MINIMIZES HAZARDS TO STS, LAUNCH FACILITIES, RANGE, AND PERSONNEL. EXTENT TO WHICH INTRODUCTION OF ENVIRONMENTAL POLLUTANTS OR OTHER DETRIMENTAL ENVIRONMENTAL IMPACTS IS AVOIDED. EXTENT TO WHICH LAUNCH DEBRIS IS MINIMIZED. | • PROPELLANT TOXICITY/EXPLOSIVE HAZARD<br>• ABORT FEASIBILITY & OPERATIONAL CONTINGENCY MODES<br>• NON-CORROSIVE, NON-TOXIC PROPELLANTS<br>• MINIMIZES RE-ENTRY DEBRIS<br>• MINIMIZES AIR, WATER, AND NOISE POLLUTION |
| RELIABILITY / SIMPLICITY | DEGREE TO WHICH LRB CONCEPTS INCORPORATE RELIABILITY ENHANCEMENTS. DEGREE TO WHICH LRB CONCEPTS REDUCE OPERATIONAL COMPLEXITY, REQUIREMENTS,OR PROCEDURES IN AN EFFORT TO STREAMLINE LRB PROCESSING. | • DESIGN MARGINS AND SIMPLICITY VS COMPLEXITY<br>• ENGINE OUT CAPABILITY<br>• EXCESS PERFORMANCE<br>• DEGREE OF SYSTEM REDUNDANCY<br>• BUILT-IN TEST AND CHECKOUT<br>• AI / EXPERT SYSTEMS FOR LAUNCH PROCESSING<br>• PROPELLANT / PROPULSION PROBLEMS<br>• MINIMIZES CONSTRAINTS, SPECIAL EQUIPMENT |
| STS COMPATIBILITY (VEHICLE) | DEGREE TO WHICH CANDIDATE LRB MINIMIZES IMPACTS TO ORBITER AND EXTERNAL TANK | • ORBITER AND ET INTERFACE MODIFICATIONS<br>• SIZE-RELATED PROBLEMS (SUCH AS WING LOADS) |
| STS COMPATIBILITY (FACILITIES) | DEGREE TO WHICH CANDIDATE LRB MINIMIZES IMPACTS TO EXISTING GROUND/LAUNCH FACILITIES | • PROCESSING/LAUNCH FACILITY MODIFICATION REQM'TS<br>• LRB PROGRAM PHASE-IN FEASIBILITY DURING ON-GOING KSC OPERATIONS |
| PERFORMANCE | ABILITY OF LRB CONCEPT TO MEET OR EXCEED REQUIRED PERFORMANCE CAPABILITY | • ENGINE / PROPULSION SYSTEM EFFICIENCY<br>• LRB GROSS LIFTOFF WEIGHT<br>• MARGINS<br>• SIZE (LRB LENGTH AND DIAMETER) |

# SECONDARY CRITERIA MATRIX

LRB

| SELECTION CRITERION | SELECTION CRITERION DEFINITION | SELECTION CRITERION ELEMENTS |
|---|---|---|
| NONRECURRING COST | INCLUDES ALL COSTS INCURRED DURING THE DESIGN, DEVELOPMENT, TEST, AND EVALUATION (DDT&E) PHASE. EXCLUDES PRODUCTION OF ALL FLIGHT HARDWARE. | • RESEARCH, DEVELOPMENT, TEST & EVALUATION<br>• DEVELOPMENT COSTS TO FLIGHT VEHICLE IOC<br>• GROUND FACILITY ACTIVATION COSTS<br>• LRB TEST FLIGHTS |
| RECURRING COST | COST (UNDISCOUNTED) STARTING WITH COMPLETION OF FIRST LRB TEST FLIGHTS AND PROCEEDS THROUGH ITS DEFINED LIFE CYCLE. INCLUDES PRODUCTION COSTS OF REUSABLE HARDWARE, RECURRING OPERATIONS COSTS, AND COSTS FOR UNRELIABILITY. | • PRODUCTION OF FLIGHT HARDWARE<br>• RECVRY, REFURB, AND RESUPPLY OF REUSABLE LRB HW<br>• ALL OPS & MAINT COSTS FOR LRB FLT AND GRD SYSTEMS<br>• COST FOR LOSSES BASED ON UNRELIABILITY |
| PROGRAM RISK | AREAS OF GREATEST COST RISK WILL BE IDENTIFIED BY ANALYZING THE SENSITIVITY OF COST TO KEY DESIGN AND PROGRAM PARAMETERS. THE LIKELIHOOD THAT REQUIRED LRB SYSTEMS CAN BE DEVELOPED AND ACQUIRED ON SCHEDULE. THE LIKELIHOOD THAT TECHNICAL ISSUES CAN BE RESOLVED. | • RISKS IN SUCCESSFULLY INTEGRATING LRB INTO STS<br>• RISKS ASSOCIATED WITH FACILITY MODIFICATIONS<br>• RISKS DUE TO DEPENDENCY ON ADVANCED TECHNOLOGY<br>• RISKS IN MANUFACTURING<br>• RISK FOR TECH DEVLPMT AND INTEG INTO LRB ON NEEDED DATE<br>• LONG LEAD PROCUREMENT<br>• ADVANCED TECHNOLOGY DEVELOPMENT<br>• RISK IN MEETING PERFORMANCE REQUIREMENTS |
| OPERATIONAL AVAILABILITY | DEGREE TO WHICH LRB CONCEPTS WILL BE OPERATIONALLY READY TO SUPPPORT STS MISSIONS | • INSENSITIVITY TO FAULTS, ENVIRONMENTS, ETC<br>• SUPPORTABILITY AND LOGISTICS<br>• PROCESSABILITY AND PRODUCIBILITY<br>• MAINTAINABILITY / REUSABLE COMPONENT TURNAROUND TIME |
| GROWTH POTENTIAL | ABILITY OF THE CANDIATE LRB CONCEPT TO ACCOMMODATE INCREASES IN STS LAUNCH REQUIREMENTS<br>ABILITY OF LRB CONCEPT TO EVOLVE TO SATISFY BOOSTER REQUIREMENTS OF FUTURE LAUNCH VEHICLE SYSTEMS | • PERFORMS INCREASED STS PAYLOAD/FLIGHT RATE REQRM'TS<br>• GROWTH COMPATABILITY FOR SDV, ALS, OR SHUTTLE II<br>• LEVEL OF LRB GROWTH POTENTIAL |

LIQUID ROCKET BOOSTER
TRADE STUDY ERB
DECEMBER 7, 1987

TRADE STUDY 1.1
FINAL ERB

# CONFIGURATION OPTIMIZATION

STUDY LEADER: DONNA SMITH

SYSTEMS ENGINEER: GREG FARMER

**GENERAL DYNAMICS**
*Space Systems Division*

# 1.1 CONFIGURATION OPTIMIZATION
## Planning Sheet 1

OBJECTIVE:

DETERMINE THE OPTIMUM LENGTH TO DIAMETER RATIO (L/D) AND CONFIGURATION OF THE LRBs TO ACHIEVE REQUIRED PERFORMANCE AND MINIMIZE STS IMPACTS (INCLUDING MAINTAINING ACCEPTABLE LOADS ON THE ORBITER WINGS)

GROUNDRULES/ASSUMPTIONS/GUIDELINES:

- LO2/H2 AND LO2/HC (RP-1, C3H8, CH4) ARE PREFERRED PUMP-FED PROPELLANTS (TS 1.5)
- L02/RP-1 IS PREFERRED PRESSURE-FED PROPELLANT (TS 1.6)
- 400 PSI OPTIMUM CHAMBER PRESSURE FOR PRESSURE-FED BOOSTER (TS 1.7)
- 4 ENGINES PER BOOSTER

# 1.1 CONFIGURATION OPTIMIZATION
## Planning Sheet 2

REQUIREMENTS:

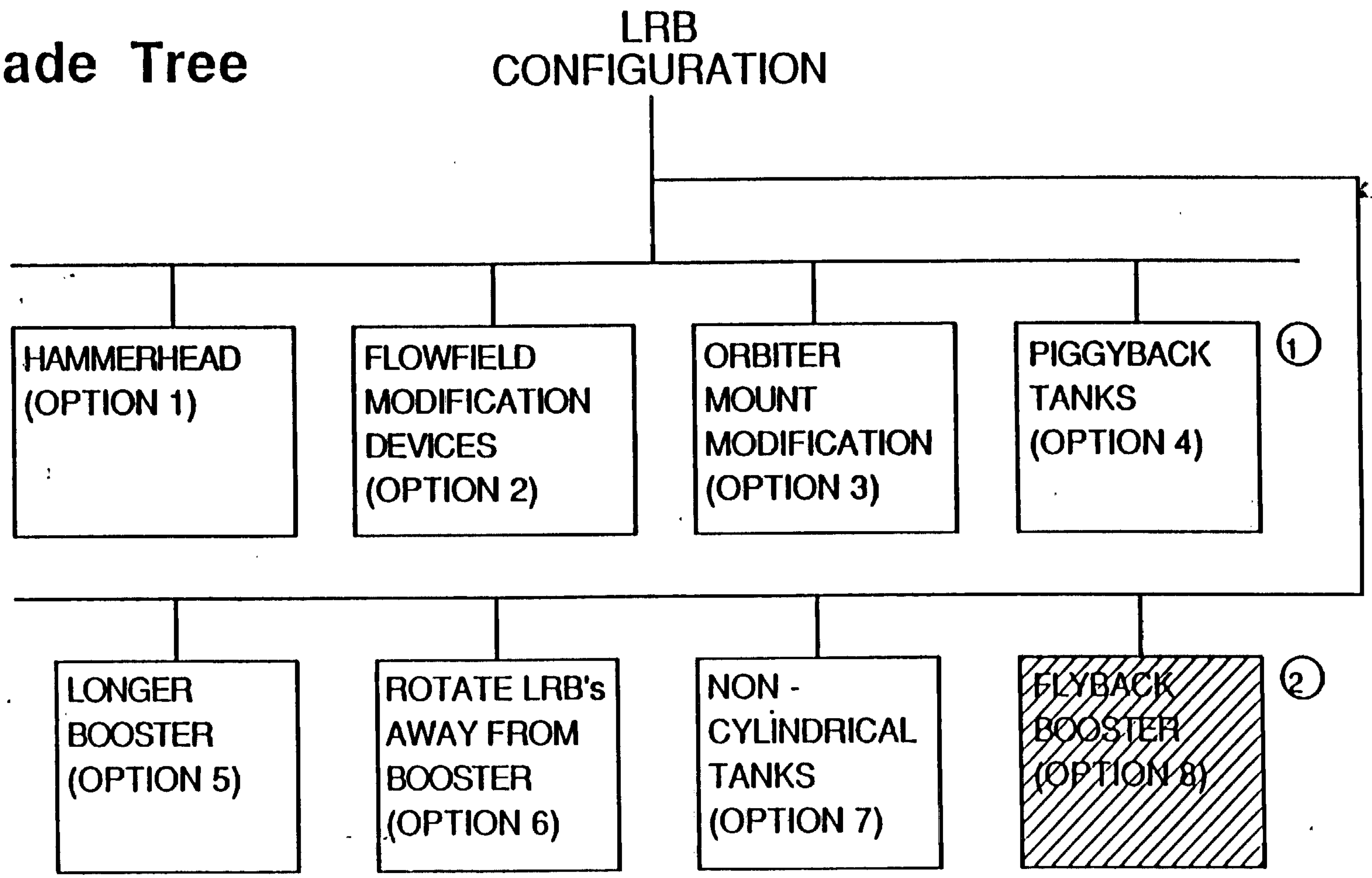
- 70 KLB PAYLOAD TO 150 NM ORBIT, 28.5 DEG INCLINATION WITH ORBITER SSME's LIMITED TO 100% PL
- 59 KLB PAYLOAD TO 150 NM ORBIT, 28.5 DEG INCLINATION WITH ORBITER SSME's LIMITED TO 104% PL

CONSTRAINTS:

- MINIMIZE IMPACTS TO ET, ORBITER, LAUNCH SITE, AND GSE
- ORBITER WING LOADS LIMITED TO CURRENT LEVELS
- STS TRAJECTORY CONSTRAINTS ON MAX Q, LIFTOFF T/W, MAX G, Q-ALPHA, ETC.
- 200 FT BOOSTER LENGTH LIMIT DUE TO VAB STRUCTURE
- 50 INCH NOZZLE EXIT DIAMETER FOR NO IMPACT TO MLP
- 90 INCH NOZZLE EXIT DIAMETER FOR NO IMPACT TO FLAMETRENCH

# 1.1 CONFIGURATION OPTIMIZATION
## Planning Sheet 4

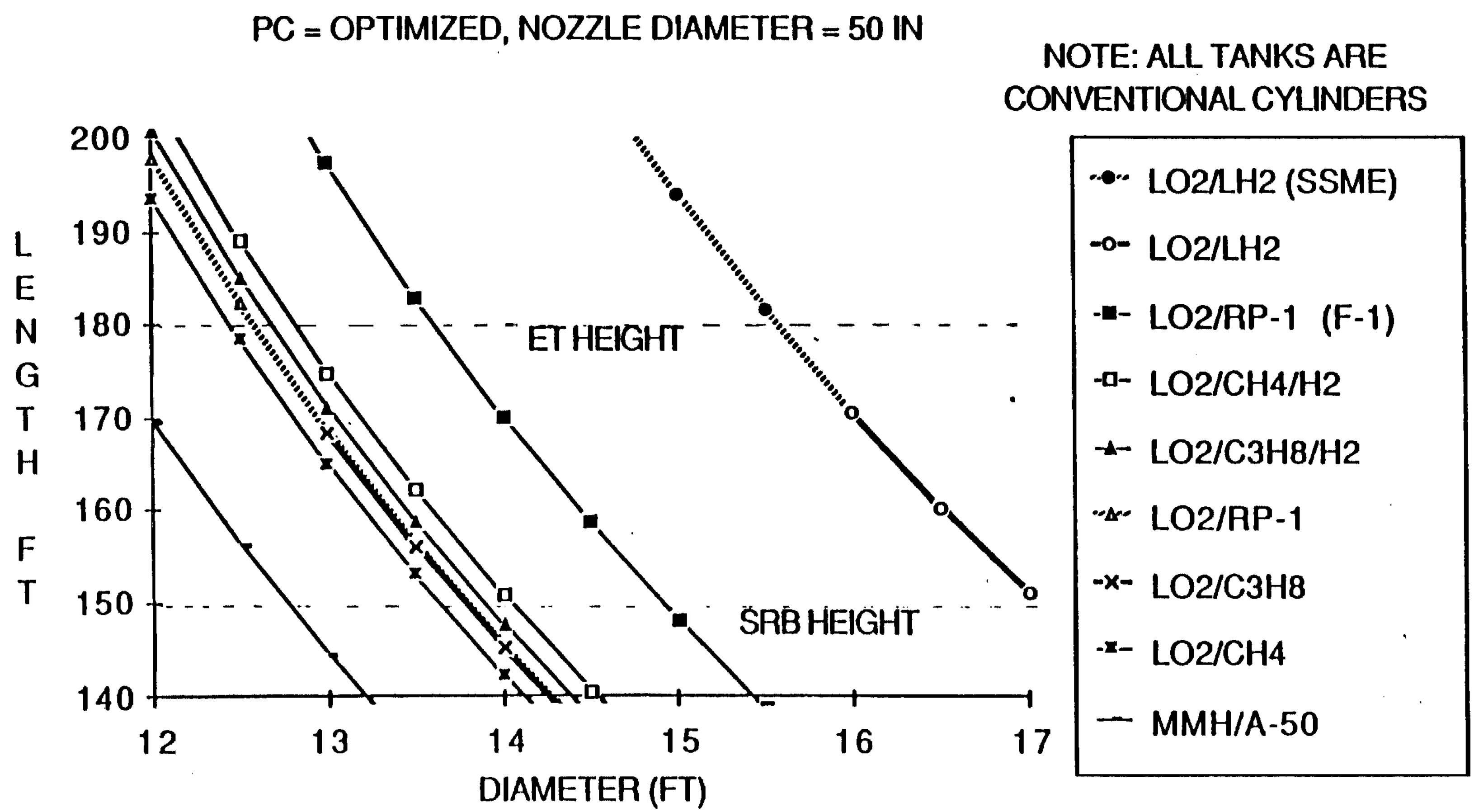
## Trade Tree



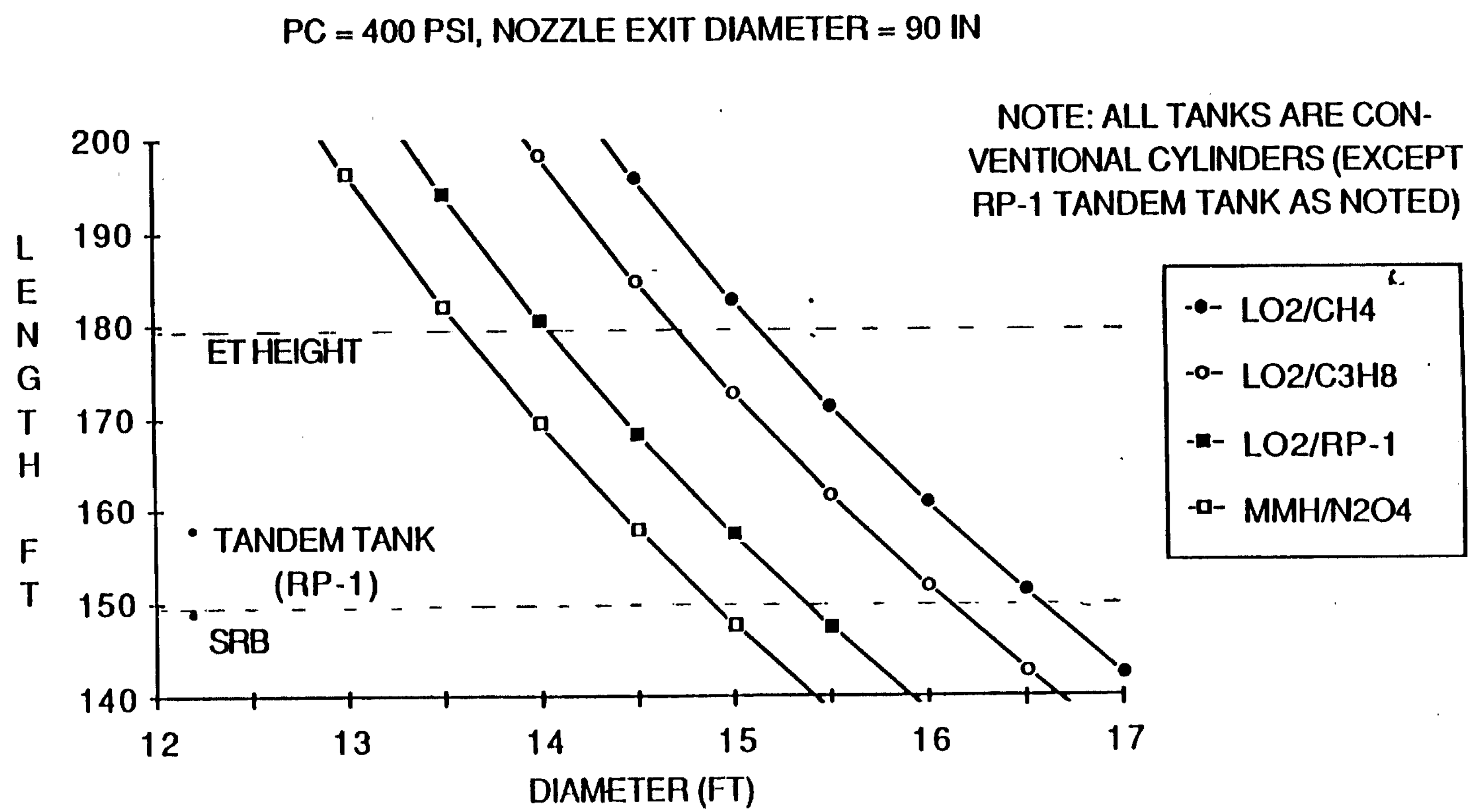

(1) VARIATIONS OF THE CONFIGURATION SHOWN WILL ALSO BE CONSIDERED

(2) ELIMINATED BY ERB DIRECTION (HIGH COST AND TECHNICAL RISK)

# 1.1 CONFIGURATION OPTIMIZATION
## Results: Pump-Fed LRB Sizes



# 1.1 CONFIGURATION OPTIMIZATION
## Results: Pressure-Fed LRB Sizes



# 1.1 CONFIGURATION OPTIMIZATION OPTION 1 EVALUATION (MSFC option #4)

LRB DIAMETER REDUCTION NEAR ORBITER WING

ADVANTAGES:

- MAINTAINS CURRENT CLEARANCE BETWEEN BOOSTER AND ORBITER WING, AS LONG AS SMALLER DIAMETER IS KEPT TO 12.2 FEET

- INCREASES AVAILABLE PROPELLANT VOLUME

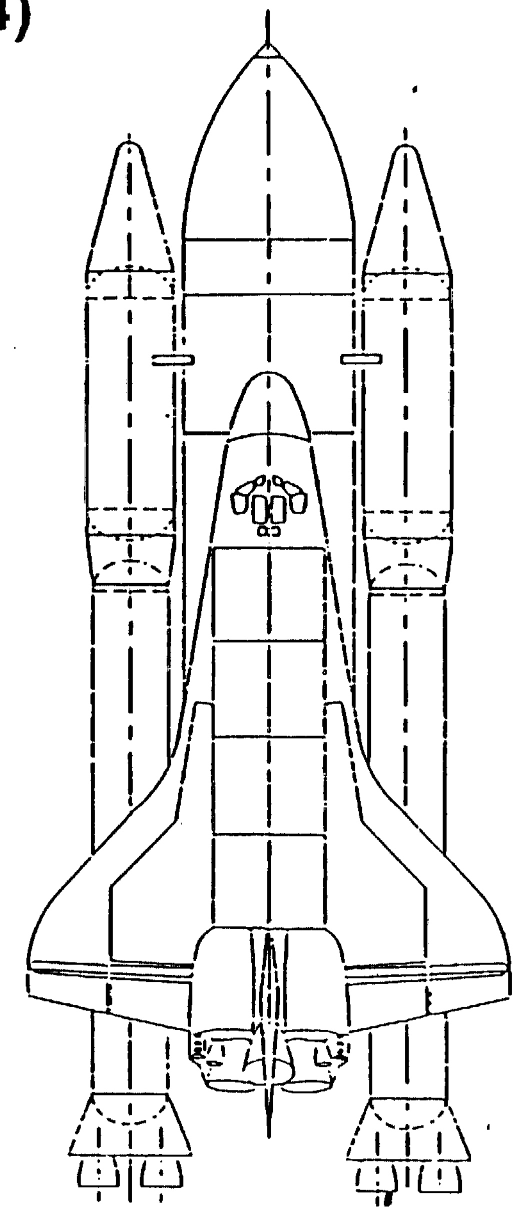
DISADVANTAGES:

- UNORTHODOX SHAPE DIFFICULT TO MANUFACTURE - HIGH DEVELOPMENT AND RECURRING COSTS

- POSSIBLE BUFFETING DURING THE TRANSONIC REGIME WOULD NEED TO BE INVESTIGATED IN UPCOMING WIND TUNNEL TESTS

- FLOW ATTACHMENT AROUND HAMMERHEAD AREA QUESTIONABLE - WOULD ALSO NEED TO BE CHECKED IN WIND TUNNEL TESTS

- THIS CONFIGURATION DOES NOT SOLVE ALL VOLUME PROBLEMS - FOR EXAMPLE, A PUMP-FED L02/LH2 BOOSTER OF 160 FT LENGTH WOULD NEED AN UPPER DIAMETER OF 23 FT



# 1.1 CONFIGURATION OPTIMIZATION OPTION 2 EVALUATION

FLOWFIELD MODIFICATION DEVICES

ADVANTAGES:

- INCREASES THE ENERGY OF THE FLOW UNDER THE WINGS IN AN EFFORT TO DECREASE THE LOADS ON THE ORBITER WINGS

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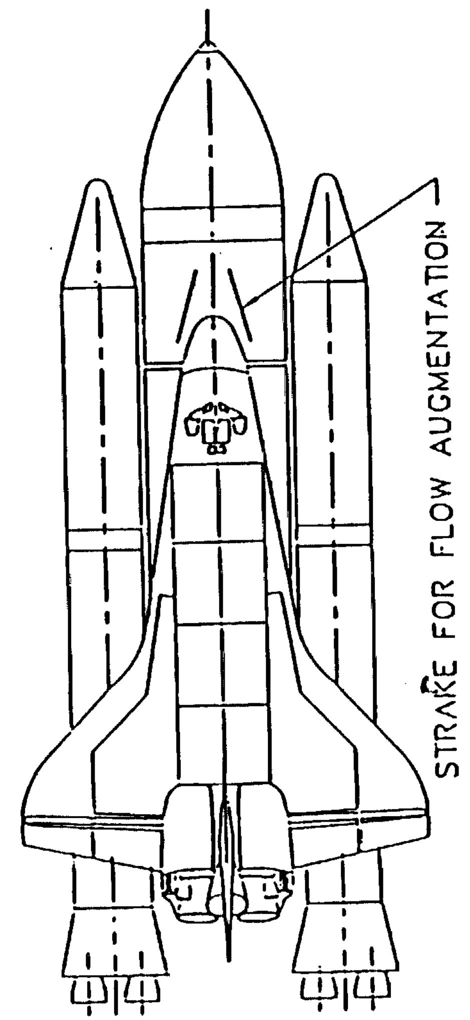
- IF THIS WORKED, A LARGER DIAMETER LRB COULD BE ACCOMODATED

DISADVANTAGES:

- AERODYNAMIC EFFECTIVENESS QUESTIONABLE - NO WIND TUNNEL TESTING PLANNED

- INVOLVES IMPACT TO EXTERNAL TANK STRUCTURE - LOADS WOULD NEED TO BE TRANSMITTED FROM THE FIN OR STRAKE TO THE ET



# 1.1 CONFIGURATION OPTIMIZATION OPTION 3 EVALUATION (MSFC options #2 & 3)

ORBITER STANDOFF MOUNT MODIFICATION

ADVANTAGES:

- MAINTAINS CURRENT CLEARANCE BETWEEN BOOSTER AND ORBITER WING BY MOVING THE ORBITER AWAY FROM THE BOOSTER

- DECREASES WING LOADS VIA TWO EFFECTS (SEPARATION DISTANCE AND ANGLE OF ATTACK)

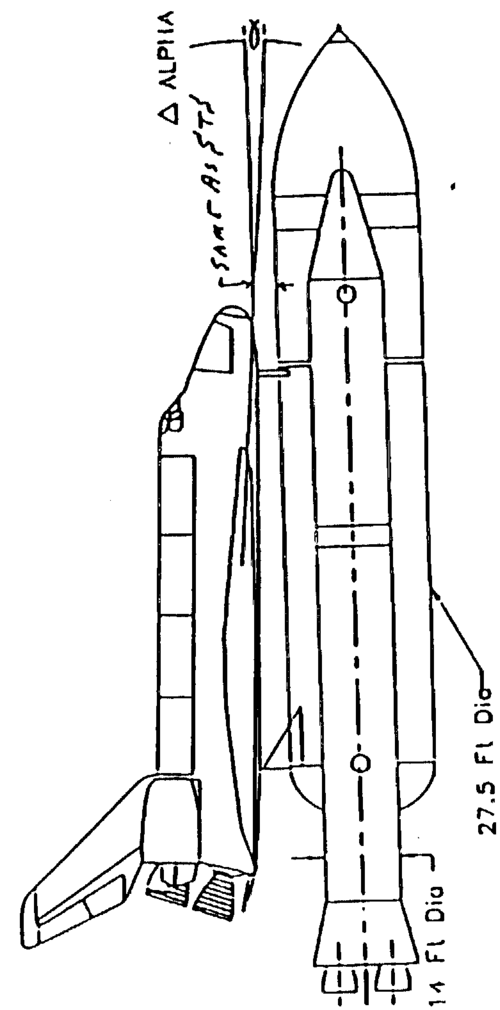
DISADVANTAGES:

- AFFECTS INTERFACE LOADS BETWEEN ORBITER AND ET

- INVOLVES REDESIGN OF ORBITER PROPELLANT FEEDLINES

- CHANGE IN ORBITER INCIDENCE ANGLE WOULD CHANGE SSME THRUST VECTOR AND THUS AFFECT THE TRAJECTORY

- MODIFICATION TO ORBITER COULD DELAY LAUNCH SCHEDULE



# 1.1 CONFIGURATION OPTIMIZATION OPTION 4 EVALUATION (MSFC option #5)

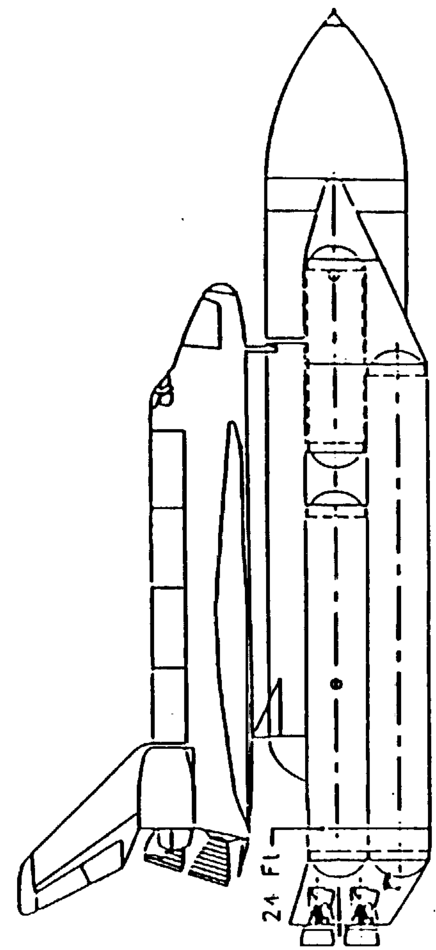
PIGGYBACK OR TANDEM TANK ARRANGEMENT:

ADVANTAGES:

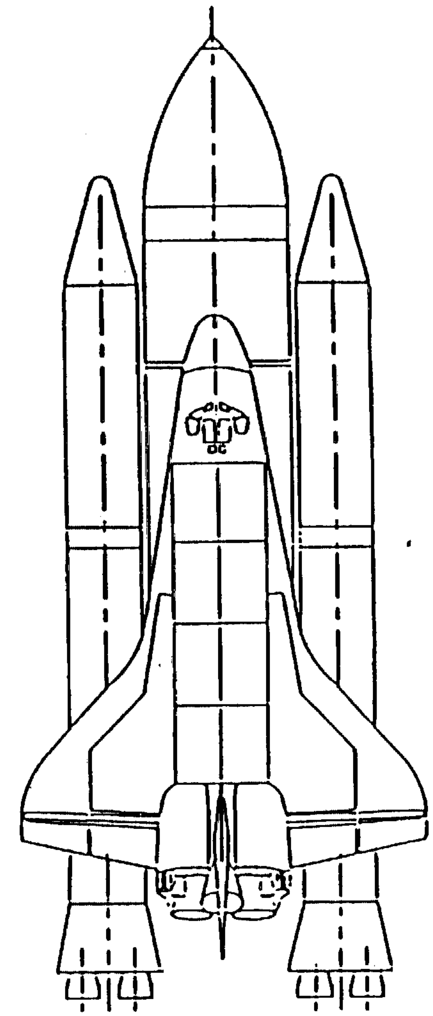
- INCREASES AVAILABLE PROPELLANT VOLUME WITHOUT CHANGING CLEARANCE BETWEEN BOOSTER AND ORBITER WING
- LRB NOZZLES COULD BE PLACED IN SAME POSITION AS CURRENT SRB NOZZLES, THUS MINIMIZING IMPACT TO FLAMETRENCH
- SIDE-BY-SIDE TANKS INCREASE THE BENDING STIFFNESS OF THE STACK, PERHAPS REDUCING THE "TWANG" PROBLEM AT IGNITION
- LARGE PERFORMANCE MARGINS AVAILABLE WITH PUMP-FED HYDROCARBON PROPELLANT CONCEPTS

DISADVANTAGES:

- COMPLEX CONFIGURATION TO DESIGN AND BUILD
- LIMITED ADAPTABILITY TO OTHER VEHICLES
- HEAT TRANSFER BETWEEN PARALLEL TANKS - ADDITIONAL INSULATION MAY BE REQUIRED FOR CRYOGENIC PROPELLANTS



# 1.1 CONFIGURATION OPTIMIZATION OPTION 5 EVALUATION



CONVENTIONAL STACKED TANKS - LONGER THAN 149 FT (D=12 FT)

ADVANTAGES:

- LOWEST IMPACT TO ORBITER, ET, AND FACILITIES OF ALL THE OPTIONS CONSIDERED
- GREATER LENGTH INCREASES AVAILABLE PROPELLANT VOLUME:

DISADVANTAGES:

- LENGTH LIMITED TO 200 FT, DUE TO VAB STRUCTURE
- DRAG AND AEROHEATING INCREASE AS BOOSTER APPROACHES ET HEIGHT
- ACCEPTANCE OF LONGER LRB DICTATED BY STRUCTURAL AND CONTROLS CONSIDERATIONS

# 1.1 CONFIGURATION OPTIMIZATION OPTION 6 EVALUATION (MSFC option #1)

ROTATING LRB'S AWAY FROM ORBITER

ADVANTAGES:

- INCREASES DISTANCE BETWEEN BOOSTER AND ORBITER WING BY ATTACHING THE LRB'S TO A DIFFERENT POINT ON THE ET, THUS ACCOMODATING A LARGER DIAMETER

- MINIMUM IMPACT TO ORBITER

- SMALL ROTATION ANGLES REQUIRED FOR HYDROCARBON PROPELLANT CONCEPTS (ABOUT ONE DEGREE)

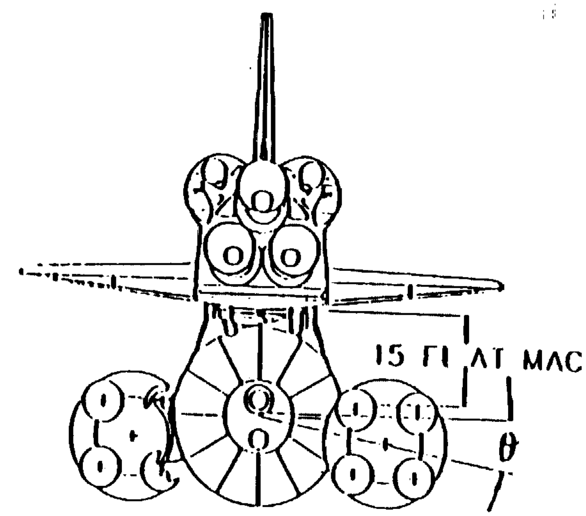
- GROWTH POTENTIAL FOR STAND-ALONE BOOSTER

- MODIFICATIONS TO ET STRUCTURE NEED NOT AFFECT STS LAUNCH SCHEDULE

DISADVANTAGES:

- INVOLVES MODIFICATION TO ET STRUCTURE AND POSSIBLE REQUALIFICATION

- MODIFICATIONS TO BOOSTER WORK PLATFORMS



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# 1.1 CONFIGURATION OPTIMIZATION OPTION 7 EVALUATION

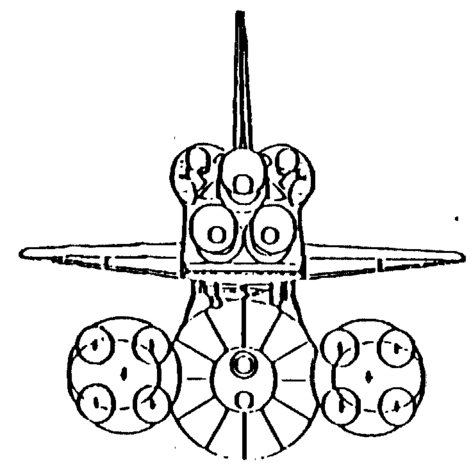
NON-CYLINDRICAL TANKS

ADVANTAGES:

- A NON-CYLINDRICAL TANK SHAPE (SUCH AS AN ELLIPTICAL CROSS SECTION) INCREASES TANK VOLUME WITHOUT CHANGING CLEARANCE BETWEEN BOOSTER AND ORBITER WING

DISADVANTAGES:

- DIFFICULT AND EXPENSIVE TO MANUFACTURE
- GREATER STRUCTURAL WEIGHT THAN AN EQUIVALENT CYLINDRICAL TANK - MORE PROPELLANT REQUIRED



# Criteria Applicability Matrix worksheet (Rev-A)

Trade Study No. 1.1



| SELECTION CRITERION | SELECTION CRITERION DEFINITION | SELECTION CRITERION ELEMENTS | Applicability |
|---|---|---|---|
| SAFETY | EXTENT TO WHICH LRB CONCEPT MINIMIZES HAZARDS TO STS, LAUNCH FACILITIES, RANGE, AND PERSONNEL | • PROPELLANT TOXICITY/EXPLOSIVE HAZARD | |
| | | • ABORT FEASIBILITY & OPERATIONAL CONTINGENCY MODES | X |
| | | • FAILURE DETECTION | X |
| RELIABILITY FEATURES | DEGREE TO WHICH LRB CONCEPTS INCORPORATE RELIABILITY ENHANCEMENTS | • DESIGN MARGINS | X |
| | | • ENGINE OUT CAPABILITY | |
| | | • EXCESS PERFORMANCE | |
| | | • DEGREE OF SYSTEM REDUNDANCY | |
| STS COMPATIBILITY | DEGREE TO WHICH CANDIDATE LRB MINIMIZES IMPACTS TO EXISTING STS. INCLUDING ORBITER, EXTERNAL TANK, AND GROUND/LAUNCH FACILITIES | • STS INTERFACE MODIFICATIONS | X |
| | | • MAINTENANCE OF STS/SRB LAUNCH CAPABILITY | X |
| | | • PROCESSING/LAUNCH FACILITY MODIFICATION REQM'TS | X |
| | | • LRB PROGRAM PHASE-IN FEASIBILITY DURING ON-GOING STS OPERATIONS | X |
| PERFORMANCE | ABILITY OF LRB CONCEPT TO MEET OR EXCEED REQUIRED PERFORMANCE CAPABILITY | • ENGINE/PROPULSION SYSTEM EFFICIENCY | |
| | | • LRB LIFT OFF WEIGHT | X |
| | | • MARGINS | X |
| NONRECURRING COST | INCLUDES ALL COSTS INCURRED DURING THE DESIGN, DEVELOPMENT, TEST, AND EVALUATION (DDT&E) PHASE. EXCLUDES PRODUCTION OF ALL FLIGHT HARDWARE. | • RESEARCH, DVLPMT, TEST & EVALUATION | |
| | | • DEVELOPMENT COSTS TO FLIGHT VEHICLE IOC | X |
| | | • GROUND FACILITY ACTIVATION COSTS | X |
| | | • LRB TEST FLIGHTS | |
| RECURRING COST | COST (UNDISCOUNTED) STARTING WITH COMPLETION OF FIRST LRB TEST FLIGHTS AND PROCEEDS THROUGH ITS DEFINED LIFE CYCLE. INCLUDES PRODUCTION COSTS OF REUSABLE HARDWARE, RECURRING OPERATIONS COSTS, AND COSTS FOR UNRELIABILITY. | • PRODUCTION OF FLIGHT HARDWARE | X |
| | | • RECVRY, REFURB, AND RESUPPLY OF REUSABLE LRB HW | |
| | | • ALL OPS & MAINT COSTS FOR LRB FLT AND GRD SYSTEMS | |
| | | • COSTS FOR LOSSES BASED ON UNRELIABILITY | |
| COST RISK | AREAS OF GREATEST COST RISK WILL BE IDENTIFIED BY ANALYZING THE SENSITIVITY OF COST TO KEY DESIGN AND PROGRAM PARAMETERS. | • RISKS IN SUCCESSFULLY INTEGRATING LRB INTO STS | |
| | | • RISKS ASSOCIATED WITH FACILITY MODIFICATIONS | |

## Criteria Applicability Matrix worksheet (Rev-A)

Trade Study No. 1.1



| SELECTION CRITERION | SELECTION CRITERION DEFINITION | SELECTION CRITERION ELEMENTS | Applicability |
|---|---|---|---|
| SCHEDULE RISK | THE LIKELIHOOD THAT REQUIRED LRB SYSTEMS CAN BE DEVELOPED AND ACQUIRED ON SCHEDULE | • RISK FOR TECH DVLPM'T AND INTEG INTO LRB ON NEED DATE | X |
| | | • LONG LEAD PROCUREMENT | |
| TECHNICAL RISK | THE LIKELIHOOD THAT TECHNICAL ISSUES CAN BE RESOLVED | • ADVANCED TECHNOLOGY DEVELOPMENT<br>• RISK IN MEETING PERFORMANCE REQUIREMENTS | X |
| OPERATIONAL AVAILABILITY | DEGREE TO WHICH LRB CONCEPTS WILL BE OPERATIONALLY READY TO SUPPPORT STS MISSIONS | • INSENSITIVITY TO FAULTS, ENVIRONMENTS, ETC | |
| | | • SUPPORTABILITY AND MAINTAINABILITY | |
| | | • PROCESSABILITY AND PRODUCIBILITY | X |
| | | • REUSABLE COMPONENT TURNAROUND TIME | |
| OPERATIONAL COMPLEXITY | DEGREE TO WHICH LRB CONCEPT REDUCES OPERATIONAL COMPLEXITY, REQUIREMENTS, OR PROCEDURES IN AN EFFORT TO STREAMLINE LRB PROCESSING | • BUILT IN TEST & CHECKOUT | |
| | | • AI/EXPERT SYSTEMS FOR LAUNCH PROCESSING | |
| | | • MISSION CONTROL SYSTEM | |
| | | • MINIMIZES HARZARDOUS OPERATIONS | |
| | | • ACCESSIBLE COMPONENTS | |
| ENVIRONMENTAL ACCEPTABILITY | EXTENT TO WHICH LRB CONCEPTS AVOID INTRODUCTION OF ENVIRONMENTAL POLLUTANTS OR OTHER DETRIMENTAL ENVIRONMENTAL IMPACTS. EXTENT TO WHICH LAUNCH DEBRIS IS MINIMIZED | • NON-CORROSIVE, NON-TOXIC PROPELLANTS | |
| | | • MINIMIZES RE-ENTRY DEBRIS | |
| | | • MINIMIZES AIR, WATER, AND NOISE POLLUTION | |
| GROWTH POTENTIAL | ABILITY OF THE CANDIATE LRB CONCEPT TO ACCOMMODATE INCREASES IN STS LAUNCH REQUIREMENTS<br>ABILITY OF LRB CONCEPT TO EVOLVE TO SATISFY BOOSTER REQUIREMENTS OF FUTURE LAUNCH VEHICLE SYSTEMS | • PERFORMS INCREASED STS PAYLOAD/FLT RATE REQM'TS | |
| | | • GROWTH COMPATIBILITY FOR SDV, ALS, OR SHUTTLE II | X |
| | | • LEVEL OF LRB GROWTH POTENTIAL | X |
| **Additional Criteria** | **Additional Criteria Definition** | | |
| | | | |

5B

# 1.1 CONFIGURATION OPTIMIZATION
## Planning Sheet 7

## Comparison Matrix

**ELIMINATED BY ERB DIRECTION**

| + Good<br>o Average<br>- Bad | Conf. 1 | Conf. 2 | Conf. 3 | Conf. 4 | Conf. 5 | Conf. 6 | Conf. 7 | Conf. 8 |
|---|---|---|---|---|---|---|---|---|
| Safety | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Reliability | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| STS Compatibility | + | 0 | - | 0 | + | 0 | 0 | |
| Performance | 0 | 0 | - | + | 0 | + | 0 | |
| Non-Recurring Cost | + | - | - | 0 | + | - | 0 | |
| Recurring Cost | - | 0 | + | - | + | 0 | - | |
| Technical Risk | - | - | 0 | 0 | + | 0 | - | |
| Operational Availability | - | 0 | + | 0 | + | 0 | - | |
| Growth Potential | 0 | + | + | - | + | + | - | |



(6A)

# 1.1CONFIGURATION OPTIMIZATION

**CONCLUSIONS:** (see "Update" - next page)

BEST CONFIGURATION APPEARS TO A COMBINATION OF ROTATION WITH INCREASED LENGTH AND DIAMETER:

- A CONVENTIONALLY-SHAPED BOOSTER, LONGER THAN THE CURRENT SRB (149 FT), BUT NOT TALLER THAN THE ET (179 FT). AVOIDS NEEDING A NEW SWING ARM FOR THE ET LOX VENT, AND MINIMIZES ET-BOOSTER SHOCK INTERACTIONS,

- DIAMETER SIZED TO MEET PROPELLANT VOLUME REQUIREMENTS, AND

- ROTATED A SMALL ANGLE AROUND THE ET TO MAINTAIN THE SAME CLEARANCE BETWEEN THE BOOSTER AND ORBITER WING

**RECOMMENDATIONS:**

- ANALYSE EFFECT OF LRB LENGTH ON LONGITUDINAL STABILITY, TO DETERMINE A LENGTH LIMIT

- DETERMINE OF STRUCTURAL LENGTH LIMIT

- OBTAIN WIND TUNNEL DATA PLOTS OF ORBITER WING SHEAR, TORSION, AND BENDING MOMENT AS A FUNCTION OF ANGLE OF ATTACK, TO DETERMINE WHICH LOAD LIMITS VEHICLE DESIGN, AND TO SEE IF THE WING LOADING PROBLEM CAN BE SOLVED BY TRAJECTORY SHAPING ALONE.

7C

UPDATE ON TS 1.1 CONFIGURATION

Configuration Optimization involves 2 related areas:

a) To avoid overloading the Orbiter wing (and other constraints) at max alpha q, non-standard LRB arrangements were considered. MSFC performed wind tunnel tests which directly related to those questions.

This trade study recommended rotating (or clocking) the large LRB so that the distance from the LRB skin to the Orbiter wing remained 15 feed at the mean aerodynamic chord. Later wind tunnel data indicated this concept is not as effective as hoped and disturbs the lateral aerodynamics. Based on subsequent wind tunnel data & loads analyses our current (5/13/88) recommendation to reliave wing loads is to reduce max alpha q for larger diameter and longer LRB's which are located on the ET centerline.

b) The second area involves optimum length and diameter dimensions. The SRMs have an L/D of 12.2. The attached memo explains why we feel this is roughly OK for LRB.

This trade is subject to updating & refinement.

LIQUID ROCKET BOOSTER
TRADE STUDY ERB
DECEMBER 7, 1987

TRADE STUDY 1.2
FINAL ERB

# ENGINE OUT/NUMBER OF ENGINES

STUDY LEADER: GOPAL MEHTA / CLYDE WILEY

SYSTEMS ENGINEER: GREG FARMER

**GENERAL DYNAMICS**
*Space Systems Division*

# 1.2 ENGINE OUT / NUMBER OF ENGINES

OBJECTIVE:

- Establish LRB engine-out requirements
- Perform an analysis to determine minimum number of engines required to satisfy engine-out considerations
- Provide guidelines for selecting number of engines

GROUNDRULES/ASSUMPTIONS/GUIDELINES:

- Safety, not cost etc., has the highest priority. Safety here means safe abort.
- Mission success (70K payload to 105 N.M. circular orbit) is the minimum goal. Nominal T/W with engine out is assumed to be 1.25 to achieve this goal
- Assume design T/W = 1.4 with no LRB engines out at L/O. (Same as current SRB case, and hence would at least keep current abort mode capability).
- All LRB engines have the same thrust.

# 1.2 ENGINE OUT / NUMBER OF ENGINES

**REQUIREMENTS:**

1) Nominal performance shall provide 70k payload to 150 x 150 nm East w/100% SSME's

2) Maintain Orbiter/ET trajectory constraints (g's,Q, etc)

3) Safety of the STS shall be improved over the current STS safety level.



**CONSTRAINTS:**

This analysis shall be limited to the LRB configurations which have one booster on each side.

# 1.2 ENGINE OUT / NUMBER OF ENGINES

## INPUTS:

- MINIMUM THRUST TO WEIGHT WITH ENGINE OUT AT L/O
  - FROM WINDLOADS AND NEAR GROUND MANEUVERING CONSIDERATIONS
  - FROM SAFE ABORT CONSIDERATION (INCLUDING FOOTPRINTS)
- DESIRED THRUST TO WEIGHT WITH ALL ENGINES AT LIFT-OFF
  - TRAJECTORY OPTIMIZATION WITH 70K P/L
  - MAXIMUM T/W ALLOWABLE BY ET AND ORBITER AT LIFTOFF
  - ENGINE COST, THROTTLING CAPABILITY REQUIRED
- FACILITY IMPACT
- ENGINE COST, WEIGHT, RELIABILITY

## OUTPUTS:

- ENGINE OUT REQUIREMENTS
- MINIMUM NUMBER OF ENGINES TO SATISFY ENGINE-OUT CONSIDERATIONS
- IMPACT OF INCREASING NUMBER OF ENGINES

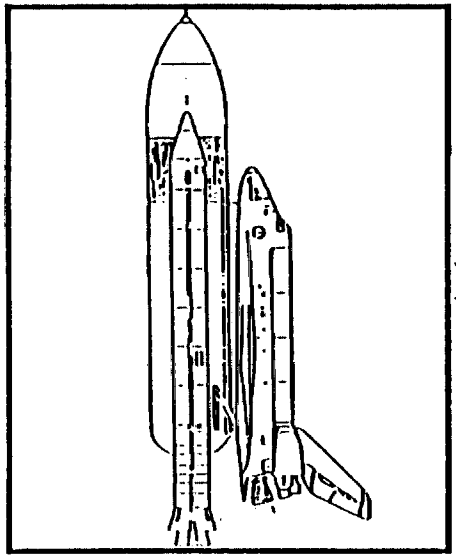
## OTHER TRADES AFFECTED:

- ALL TRADES

# 1.2 ENGINE OUT / NUMBER OF ENGINES

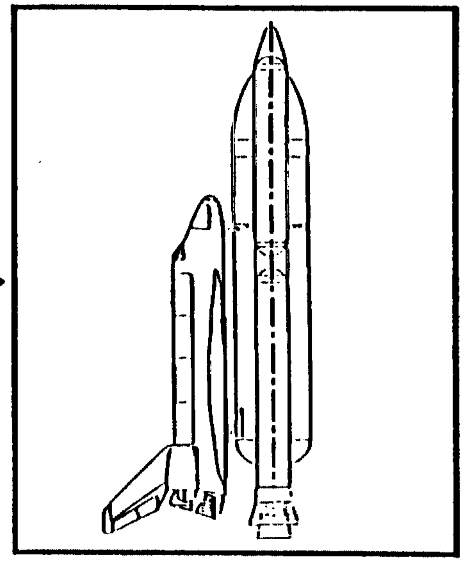
## RESULTS - ENGINE OUT CONSIDERATION

QUALITATIVE



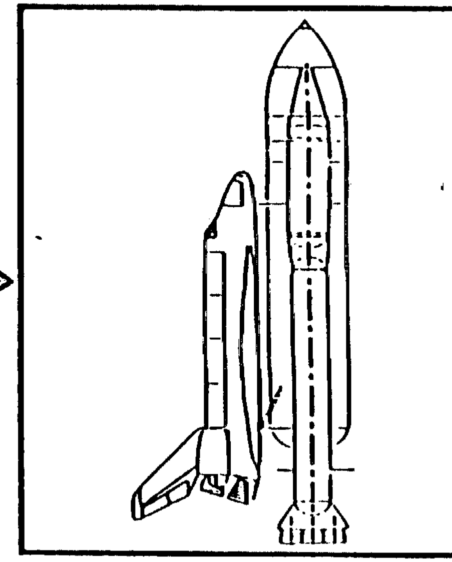
SRB (CURRENT)

- SIMPLE
- CURRENT CONFIGURATION (NO IMPACT)
- NO THROTTLING FLEXIBILITY
- NO ABORT MODE DURING BOOST
  - FAILURE CATASTROPHIC



SINGLE ENGINE LRB

- MORE COMPLEX
- LOWER DENSITY IMPULSE (AND HENCE WOULD HAVE IMPACT ON STS)
- THROTTLING FLEXIBILITY (BETTER TRAJECTORY OPT. AND CONTROL)
- LIMITED ABORT MODE DURING BOOST
  - ENGINE CUT-OFF POSSIBLE IN EMERGENCY
  - SAFER
  - STS SYSTEM RELIABILITY MAY INCREASE



MULTI-ENGINE LRB

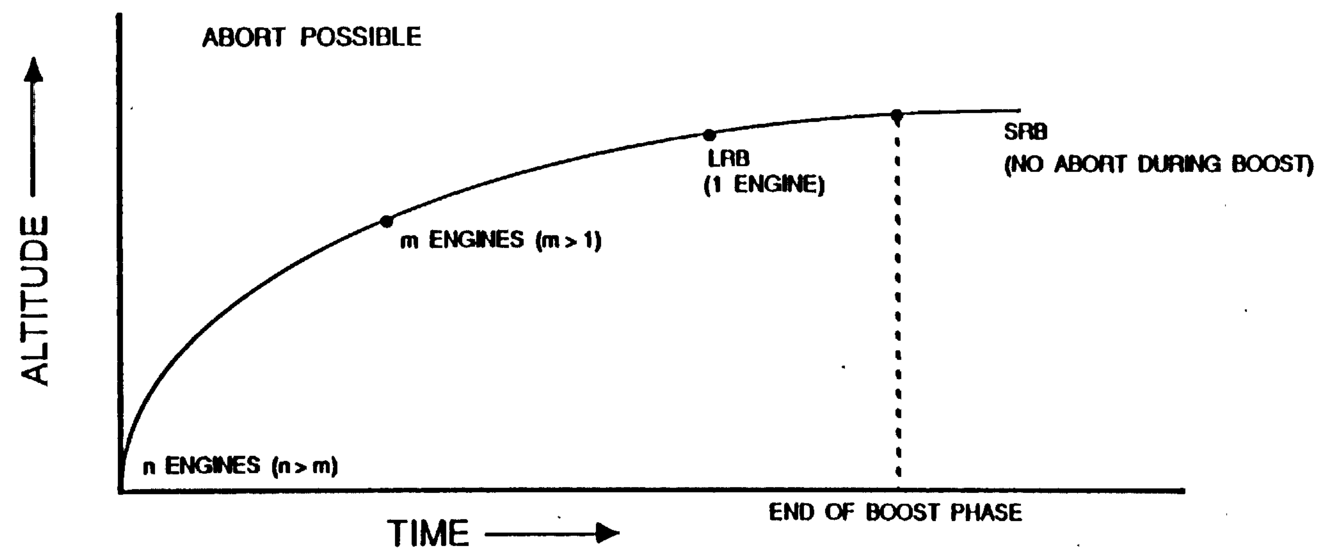
- INCREASED COMPLEXITY
- LOWER DENSITY IMPULSE (AND HENCE WOULD HAVE IMPACT)
- THROTTLING FLEXIBILITY (BETTER TRAJECTORY OPTIMIZATION & CONTROL)
- INCREASED ABORT FLEXIBILITY / SAFETY
  - SAFE ABORT WITH ENGINE OUT-CAPABILITY POSSIBLE AT ALL TIMES
  - MISSION SUCCESS POSSIBLE WITH ENGINE OUT CAPABILITY FOR SOME CASES
  - STS SYSTEM RELIABILITY MAY INCREASE

# 1.2 ENGINE OUT / NUMBER OF ENGINES



RESULTS - ENGINE OUT CONSIDERATION

QUALITATIVE (CONTINUED)



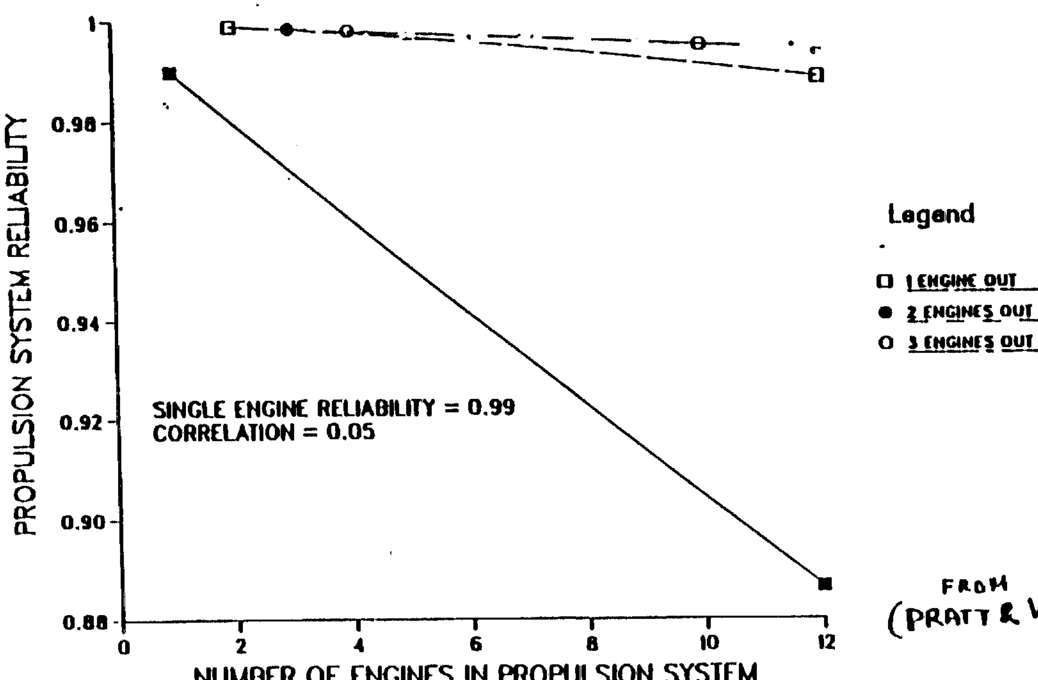

- GOING FROM SRB TO LRB SATISFIES REQUIREMENT OF INCREASED SAFETY
  - WITH SHUTDOWN
- SINGLE ENGINE LRB PROVIDES SAFE ABORT OVER PART OF THE BOOST PHASE
- MULTIPLE ENGINES (WITH ENGINE OUT CAPABILITY) ON LRB CAN PROVIDE SAFETY THROUGHOUT THE WHOLE BOOST PHASE

# 1.2 ENGINE OUT / NUMBER OF ENGINES

## RESULTS - ENGINE OUT CONSIDERATION

## RELIABILITY ANALYSIS

- ANALYSIS BASED ON R = 0.99 AND CORRELATION OF 0.05 (EXAMPLE)
- PRESSURE FED SHOULD HAVE HIGHER RELIABILITY THAN PUMP FED BECAUSE OF LACK OF TURBO-MACHINERY
- RELIABILITY SHOULD BE BASED ON AFTER IGNITION AND TRANSIENT EFFECTS (BECAUSE HOLD DOWN CAPABILITY OF LRB)
- TREND, NOT ABSOLUTE NUMBERS, IMPORTANT AT THIS POINT




FROM (PRATT & WHITNEY PRESENTATION)

BASICALLY SAYS ONE ENGINE OUT CAPABILITY SHOULD BE A GOAL FOR SMALLER NUMBER OF ENGINES AND TWO ENGINES OUT FOR GREATER NUMBER.

# 1.2 ENGINE OUT / NUMBER OF ENGINES

RESULTS - ENGINE OUT CONSIDERATION

QUANTIFY (SUBJECTIVE) PRELIMINARY REQUIREMENT AS:

| ENGINE TYPE | NUMBER OF ENGINES | ENGINE OUT CAPABILITY AT LIFT-OFF |
|---|---|---|
| F-1 ENGINE | 2 | 1 LRB ENGINE OR 1 SSME |
| ALL OTHER ENGINES | > 2 | 1 LEFT LRB ENGINE & 1 RIGHT LRB ENGINE<br>OR 1 LRB ENGINE & 1 SSME ENGINE |

RELIABILITY - REQUIREMENT OR ASSUMED REQUIREMENT ON FAILURE TOLERANCE:

NONE

# 1.2 ENGINE OUT / NUMBER OF ENGINES

## MINIMUM NUMBER OF ENGINES

## ANALYSIS (RESTRICTED HERE TO LRB ENGINE FAILURE; CAN BE EASILY EXTENDED)

DEFINITIONS

$T_{wd}$ = DESIGNED THRUST/WEIGHT AT LIFTOFF

$T_{wm}$ = MINIMUM THRUST/WEIGHT AT LIFTOFF

$F_{boost}$ = TOTAL BOOSTER THRUST

$F_{ssme}$ = TOTAL SSME THRUST

N = TOTAL NUMBER OF BOOSTER ENGINES

Z = TOTAL NUMBER OF ENGINES OUT

DEVELOPMENT

$$T_{wd} = \frac{F_{boost} + F_{ssme}}{W} \qquad T_{wm} = \frac{\frac{F_{boost}}{N}(N-Z) + F_{ssme}}{W}$$

$$T_{wd} / T_{wm} = (F_{boost} + F_{ssme}) / \left(\frac{F_{boost}}{N}(N-Z) + F_{ssme}\right) \Rightarrow \frac{F_{boost}}{N}(N-Z) + F_{ssme} = (F_{boost} + F_{ssme})\frac{T_{wm}}{T_{wd}}$$

$$\frac{F_{boost}}{N}(N-Z) = (F_{boost} + F_{ssme})\frac{T_{wm}}{T_{wd}} - F_{ssme} \Rightarrow F_{boost} - Z/N\, F_{boost} = (F_{boost} + F_{ssme})\frac{T_{wm}}{T_{wd}} - F_{ssme}$$

$$Z/N\, F_{boost} = F_{boost} - (F_{boost} + F_{ssme})\frac{T_{wm}}{T_{wd}} + F_{ssme} \Rightarrow N = Z\, F_{boost} / \left\{ F_{boost} - (F_{boost} + F_{ssme})\frac{T_{wm}}{T_{wd}} + F_{ssme} \right\}$$

# 1.2 ENGINE OUT / NUMBER OF ENGINES

## MINIMUM NUMBER OF ENGINES ANALYSIS (CONTINUED)

HENCE MINIMUM NUMBER OF ENGINES CAN BE DETERMINED BY A SIMPLE EQUATION

$$N = \frac{Z}{(1 + F_{ssme} / F_{booster})\ (1 - T_{wm} / T_{wd})}$$

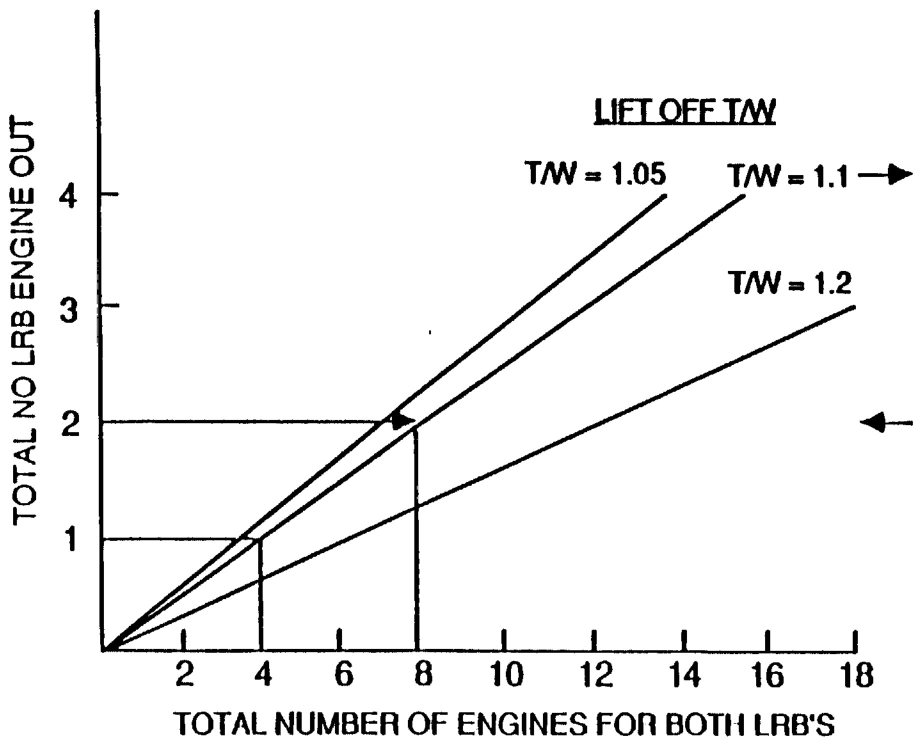
IF WE KNOW :

$Z$ = NUMBER OF BOOSTER ENGINES OUT
$F_{ssme}$ = TOTAL ORBITER THRUST
$F_{booster}$ = TOTAL BOOSTER THRUST
$T_{wm}$ = T / W WITH ENGINE OUT
$T_{wd}$ = DESIGN T / W

# 1.2 ENGINE OUT / NUMBER OF ENGINES

## MINIMUM NUMBER OF ENGINES

## RESULTS:




- LRB FAILURE EFFECTS*:
  - 1 LRB OUT = 2 ENG/LRB (4 TOTAL) REQD
  - 2 LRB OUT = 4 ENG/LRB (8 TOTAL) REQD

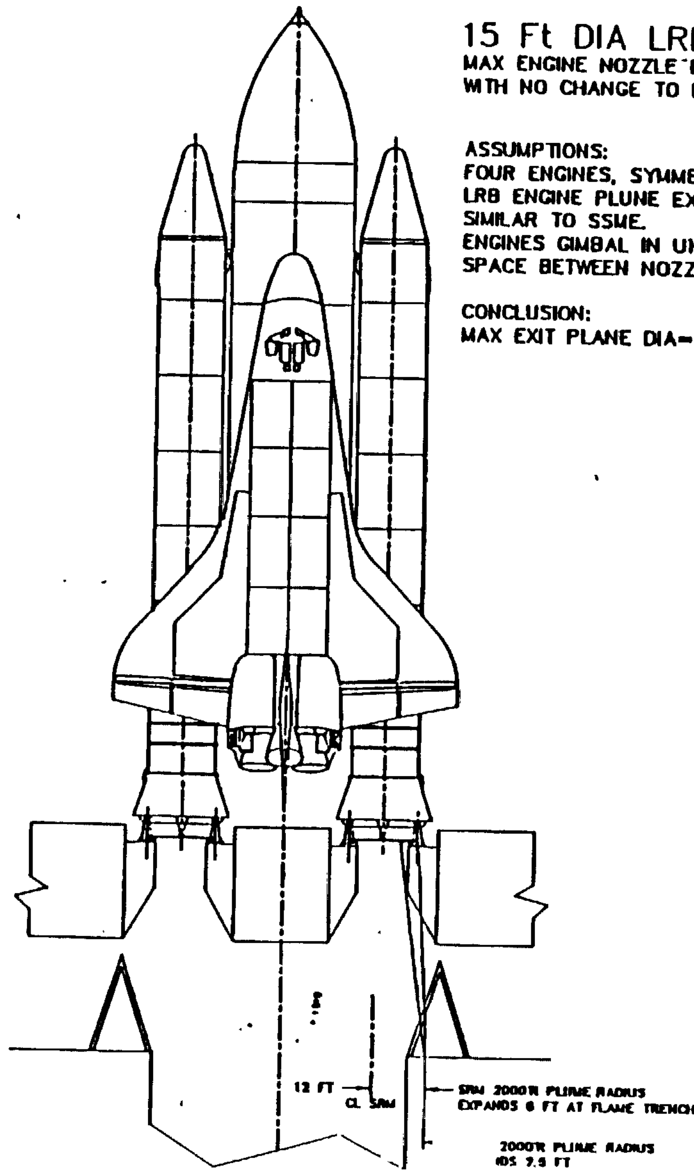
  *NOTE: APPLICABLE TO L/O T/W = 1.05 & 1.1

- ASSUME DESIGN (NO LRB FAILURE) T/W = 1.4 SATISFIES (CURRENT) SSME FAILURE ABORT CAPABILITY

  ASSUME LRB TOTAL THRUST CONSTANT @ 3.0 MLBF EA.

# 1.2 ENGINE OUT / NUMBER OF ENGINES

## FACILITY IMPACT:




15 Ft DIA LRB, 4 ENGINES/LRB
MAX ENGINE NOZZLE EXIT PLANE DIAMETERS WITH NO CHANGE TO ETR FLAME TRENCH.

ASSUMPTIONS:
FOUR ENGINES, SYMMETRICAL AROUND LRB CL.
LRB ENGINE PLUME EXPANSION IS SIMILAR TO SSME.
ENGINES GIMBAL IN UNISON EVEN WITH ONE OUT.
SPACE BETWEEN NOZZLES IS 10% OF EXIT DIA.

CONCLUSION:
MAX EXIT PLANE DIA=7.5 FT (90 IN.)

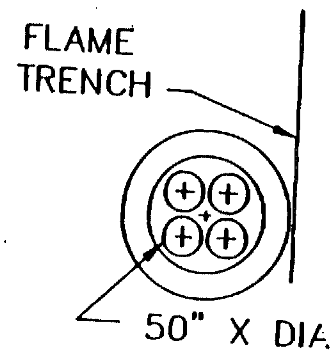
DAVE HAYS
NOV 18,1987
FILE MIP-LRB

# 1.2 ENGINE OUT / NUMBER OF ENGINES

## FACILITY IMPACT:

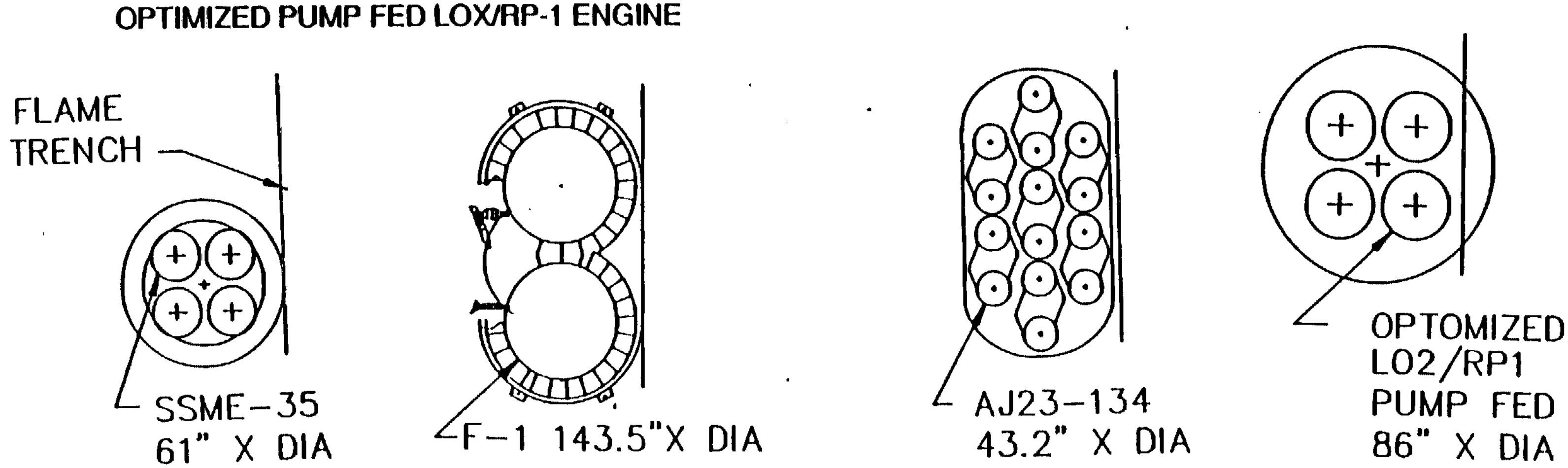
INITIALLY THOUGHT TO BE DRIVER. BUT NOT SO IF USE IS MADE OF RECTANGULAR SHAPE OF FLAME TRENCH.

- NO CHANGE IN MLP & FLAME TRENCH: ALLOWS 4-50" EXIT DIA NOZZLES. MOST PUMP FED, EXCEPT RP-1, SHOW LITTLE SENSITIVITY TO NOZZLE SIZE OPTIMIZATION BECAUSE CRAMER PRESSURES ALLOWED/SELECTED ARE HIGH




(10° GIMBAL ANGLE)

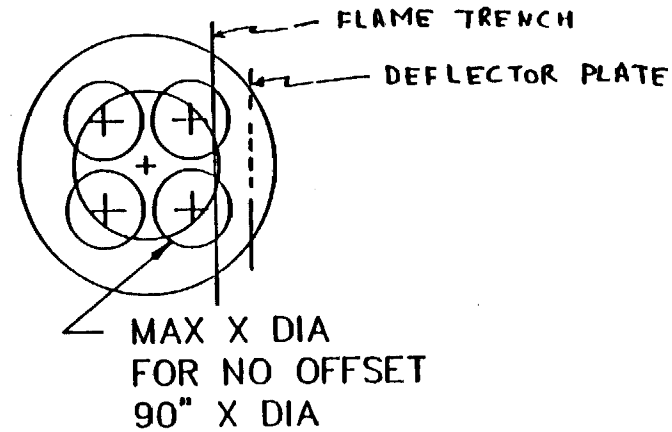
- MODIFIED/NEW MLP BUT NO CHANGE IN FLAME TRENCH. (1) ALLOWS EXISTING ENGINES PUMP FED (4-109% SSME35, 2-F-1 ENGINES, 10-RJ23-13L ENGINES) AND BACK PRESSURE OPTIMIZED PUMP FED LOX/RP-1 ENGINE



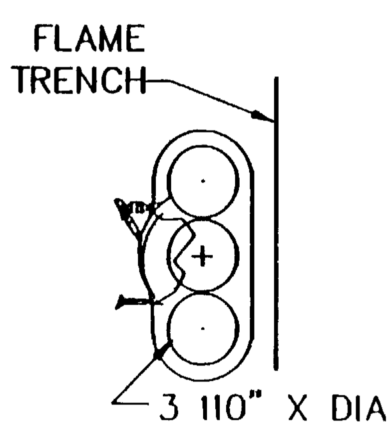
# 1.2 ENGINE OUT / NUMBER OF ENGINES

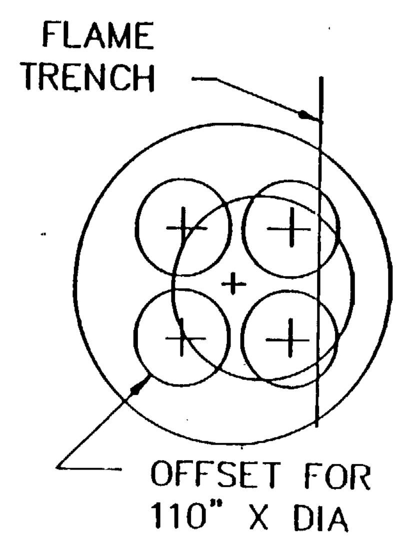
**FACILITY IMPACT (Contd):**

(2) ALLOWS 4-90% EXIT DIA NOZZLES. ALL PRESSURE FED SYSTEMS AT OPTIMIZED CHAMBER PRESSURE SHOW LITTLE SENSITIVITY TO NOZZLE SIZE OPTIMIZATION BECAUSE OF REASONABLE EXPANSION RATIO.




- OTHER ARRANGEMENTS CAN BE USED TO INCREASE THE EXIT DIAMETER



# 1.2 ENGINE OUT / NUMBER OF ENGINES

## DESIRED NUMBER OF ENGINES

| OPTIMIZATION PARAMETERS | REMARKS |
|---|---|
| • FACILITY IMPACT | MINIMUM IMPACT OF INCREASE IN ENGINES (WITHIN REASONABLE BOUND) |
| • SYSTEM WEIGHT | ENGINE SYSTEM WT. FIRST INCREASES AND THEN DECREASES |
| • CONTROL AUTHORITY | LESS GIMBAL & THROTTLING REQUIREMENT WITH MORE NUMBER OF ENGINES |
| • COST PER BOOSTER | WILL HAVE MINIMAL IMPACT AT CERTAIN NUMBER OF ENGINES<br>(BECAUSE OF TESTING, MANUFACTURING, ETC.) |
| • GROUND OPS | INCREASES WITH NUMBER OF ENGINES |
| • COMPLEXITY/RELIABILITY | COMPLEXITY INCREASES BUT RELIABILITY OF LRB MAY NOT SUFFER BECAUSE OF INCREASED ENGINES OUT CAPABILITY |

# 1.2 ENGINE OUT / NUMBER OF ENGINES

## SUMMARY

- AN LRB INHERENTLY PROVIDES ENHANCED SAFE ABORT OVER SRB

- MULTI-ENGINE LRB ARE PREFERRED CONFIGURATION AS THEY CAN PROVIDE ENGINE OUT CAPABILITY, WHICH RESULTS IN GREATER RELIABILITY (GREATER CHANCE OF SAFE ABORT AND MISSION SUCCESS)

A1

- AN ASSUMED REQUIREMENT FOR ENGINE OUT SUGGESTED IS

| NUMBER OF ENGINES | ENGINES | ENGINES OUT |
|---|---|---|
| 2 | F-1 | 1 LRB OR 1 SSME |
| > 2 | NEW | 1 ENGINE/BOOSTER (TOTAL 2) OR 1 LRB & 1 SSME |

- FOR INITIAL TRADES, USE MINIMUM NO. OF ENGINES WHICH GIVES ABOVE MENTIONED ENGINE OUT CAPABILITY.

UPDATE ON T.S. 1.2 NUMBER OF ENGINES

The attached memo is a continuation and update of the original trade study on the number of engines. It was initially assumed that the Shuttle crew must be able to safely perform a contingency abort if one LRB engine failed. This leads to the basic requirement for a minimum of 2 engines per LRB.

We believe that LRBs must have superior mission reliability to SRBs, if the program is to be "sold". Therefore we are currently (5/13/88) sizing LRBs to meet the extra requirement of abort to orbit with one engine out. Minimum thrust-to-weight at launch to clear the tower with one engine out and nominal T/W at launch for minimum GLOW are vital considerations. So is the throttle range.

The attached memo summarizes our belief that 4 engines are the best (safe and reliable) choice for LRB. More recent performance runs with new constraints for the ET aft bulkhead are showing requirements for throttling >35% which impacts engine costs and may be a development ris for LOX/RP.

This trade should be reevaluated.

To: Dan Heald

ORIGINAL PAGE IS
OF POOR QUALITY

4/1/88

From: Gopal Mehta & Paul R. Brennan

Subject: Assessment Of Number Of Engines Required

Reference: Memo L. Wear 3/18/88. Results Of LRB Configuration Selection Review

This memo is a response to the above action item, and presents our reassessment of the number of engines per LRB. 3, 4 and 6 engine arrangements as shown in Figure 1.0 were evaluated. The results discussed herein are mainly based upon analyses conducted using the LO2/RP-1 pump-fed booster. However the trends represented are considered valid for the other selected LRB concepts. Any significant differences between concepts are discussed. Based on results to date, we conclude that 4 engines should be used on all three LRB concepts.

The criteria by which the number of engines was chosen are summarized below. These criteria are the same as those used for the configuration trade studies, and are ranked in order of importance.

1) Safety/Reliability: The reliability of the propulsive system to accomplish a given mission diminishes as the number of engines increases. To improve safety, or better the chances of saving the crew and payload in the event of an engine failure, it is desirable to have engine-out capability. If engine out capability is designed into the booster, the reliability of the propulsive system to meet the desired mission is improved. Examine Figure 2.0. The GD goal is to size the LRBs such that if a booster engine fails during ascent, it is still possible for the orbiter to deliver full payload to a reduced "safe" orbit and return the crew. Table I shows reliability values with and without engine-out capability using typical pump-fed and pressure-fed reliability data. Because high reliability is desired, the basic conclusion can be drawn that a four engine arrangement is preferred over a six engine arrangement.

2) STS Compatibility: The quantity of LRB engines used affects the MLP/Flame trench, plume/base heating, aerodynamic drag, control of the mated vehicle, and ground/flight operations.

For our initial trade studies, free plume expansion in the MLP was assumed to be similar to the SSMEs, and the LRB nozzle diameter was constrained such that the plume from the LRB engines struck the flame deflectors located over the flame trench in the same manner as the SRBs. This low risk approach allowed a maximum exit diameter of 90 inches. Optimum pump-fed engine performance can be achieved within this limitation. However, the pressure-fed engine performance (for 4 engine LRBs) optimizes with nozzle diameters over 90 inches (see Figure 3.0); if 6 engines are used on the LRBs it is easier to optimize engine performance within the 90 inch nozzle limit. Because the 4 engine pressure-fed booster optimizes with nozzle diameters greater than 90 inches, we asked our subcontractors, PRC and Rocketdyne, to assess the possibility of using nozzle diameters greater than 90 inches. We feel that by shaping the MLP flamehole side walls and modifying the flame deflectors it will still be possible to channel the exhaust into the flame trench. However, scale model testing will be required to verify/prevent overpressure wave impingement on the engines or interference with their operation. Hence, although 6 engines are better suited for ~~for~~ the 90 inch diameter limit, currently no major impact is foreseen in increasing the exit diameter beyond 90 inches to get optimum size/performance using 4 engines.

An initial assessment made by Eagle Engineering suggests that the plume radiative heating to the orbiter body flap with engines aligned in a vertical row, rather than a clustered about the booster centerline is more severe (~10%). To fit within the geometry of the flame trench, the row layout is better suited for the 6 engine case (Examine Figure 1.0). However, for either engine layout (in a row or clustered around the centerline), the LRB base heating rate will be approximately ~30% less than the current SRBs.

The aerodynamic drag of a 3 or 6 engine LRB is expected to be greater than that of the same booster using 4 engines due to the larger aft skirt area (assuming the 6 engines are aligned in a row as presented in Figure 1.0). Presently vehicle control does not pose any problem for all three number of engine options. For comparison, engine out gimbal angle were calculated using the RP-1 pressure-fed booster with 3,4, and 6 engines. The worst case was the three engine case, and the largest gimbal angle for engine out at maximum dynamic pressure was less than 5 degrees.

Ground/flight operational complexity will increase with increasing number of engines. In terms of ground operations, additional test and checkout will be required for additional engines, actuators, feedlines and avionics. In terms of flight operations, additional software development will be required as the number of engines increases. Additional costs due to increased operational complexity as the number of engines multiplies have not been evaluated.

3) Performance: In this section, impact on Emergency Power Levels (EPL), vehicle weight, engine weight, and throttling requirements required are discussed.

As shown in Figure 4.0, the booster lift-off weight minimizes at nominal T/W = 1.52 for a 4 engine LOX/RP-1 pump-fed booster. To achieve an ATO (due to engine-out at liftoff) without changing the size of the LRB and using approximately balanced thrust during ascent, one needs a T/W=1.25 at liftoff; the T/W required for ATO is sufficient to clear the pad in the event of wind drift as analyzed by LEMSCO (i.e., $T/W_{ATO} > 1.2$). The 1.25 T/W requirement means an emergency power level (EPL) is needed for the 4 engine case as calculated by:

$$T/W_{EPL} = \frac{((T/W)_{ATO} * \text{Vehicle Wt} - T_{SSME}) * 8/6 + T_{SSME}}{\text{Vehicle Weight}}$$

$$= 1.58$$

Thus a slight up-throttle capability (~6%) is needed. Extrapolating this data to 6 and 3 engine cases, it seems no extra EPL is needed for the 6 engine case, and the $T/W_{EPL}$ for the 3 engine case is 1.7. If the nominal T/W is on the order of 1.5 then this increase in thrust level represents additional engine cost and weight. One can view the impact of ATO on the number of engines required in another fashion. If no EPL is provided, then the booster must be sized to a T/W which, with an engine out at liftoff, provides a T/W =1.25. For the 4 engine booster this nominal T/W would be 1.58, for 3 engines it would be 1.7 and for 6 engines it would be 1.49. If one assumes that the relationship shown on Figure 3.0 is largely independent of the number of engines used, then for the six engine case the optimum T/W of 1.52 can be used at liftoff and still have ATO capability with engine-out. However, for the 4 engine case there is penalty in weight for sizing the booster at a T/W of 1.58 rather than 1.52 (<5000 LBs). The penalty in weight for the 3 engine case is much larger. The difference between sizing at a T/W of 1.7 rather than 1.52 is approximately 35,000 lbs. Thus there is no impact for 6 engines, a very slight impact for 4 engines, and a large impact for 3 engines. Similar trends hold for pressure-fed engines if optimum expansion ratios can be used (see the discussion on "STS Compatibility"), except that any EPL requirement imposes larger cost and weight penalties than for pump-fed engines due to the need for higher tank pressures.

The weight of the engines increases slightly with increasing number of engines (after 4). Yet even with inclusion of accessories, the difference in weight is quite small.

The approximate throttling range for various numbers of engines (with and without engine-out) are shown in Table I. An accepted rule of thumb in the industry is that 35-40% throttling is easily achievable. Any higher range imposes significant technological risk and cost. For the RP-1 pump-fed booster used in this comparison, throttle ranges for both the 4 and 6 engine configurations fall within this range, but the 3 engine case requires ~49% throttling.

4) Cost: The approximate change in engine DDT&E cost and manufacturing cost with change in number of engines are shown in Table I. As expected, DDT&E cost per engine decreases with an increase in the number of engines used per booster. There is not much of a change in engine manufacturing cost per LRB as the number of engines changes.

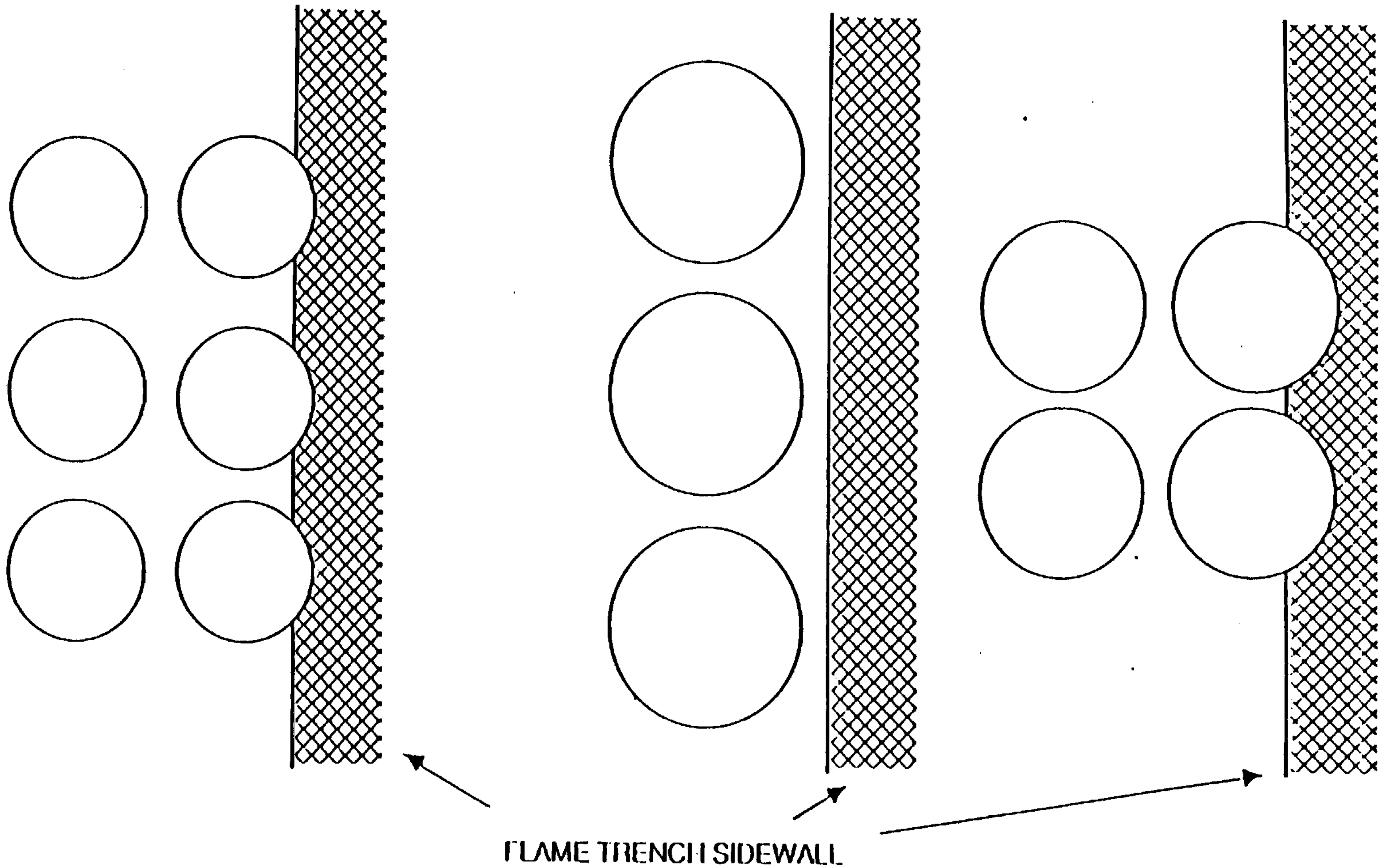
Conclusion Safety and reliability are improved if the minimum multiple number of engines is used per LRB (while still retaining engine-out capability). A 6 engine configuration is poorer than 4 engines in terms of safety/reliability, overall vehicle complexity, and STS compatibility. As safety, reliability, and STS compatibility are the premier criteria for judging options on this program, we conclude that 4 engines per LRB is the best number of engines to use.

Paul R. Brennan

Paul R. Brennan

G Mehta

Gopal Mehta




Figue 1.0 - Engine Layouts Considered

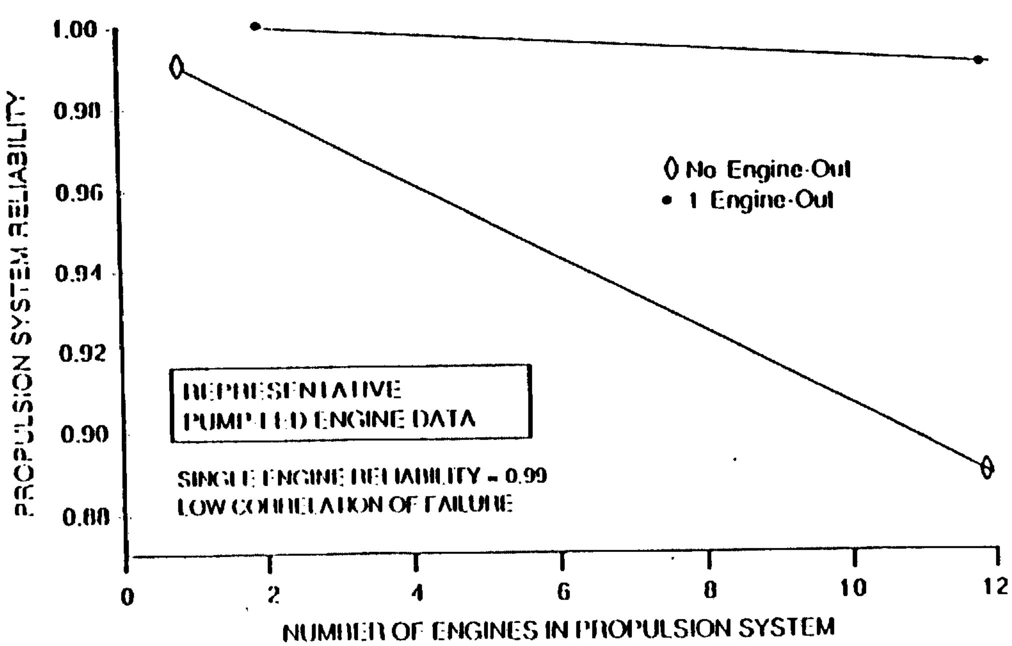



Figure 2.0 - Number of Engines vs. Propulsion System Reliability for a typical pump-fed engine system

FIGURE 2.0 - PERFORMANCE VS. EXPANSION RATIO

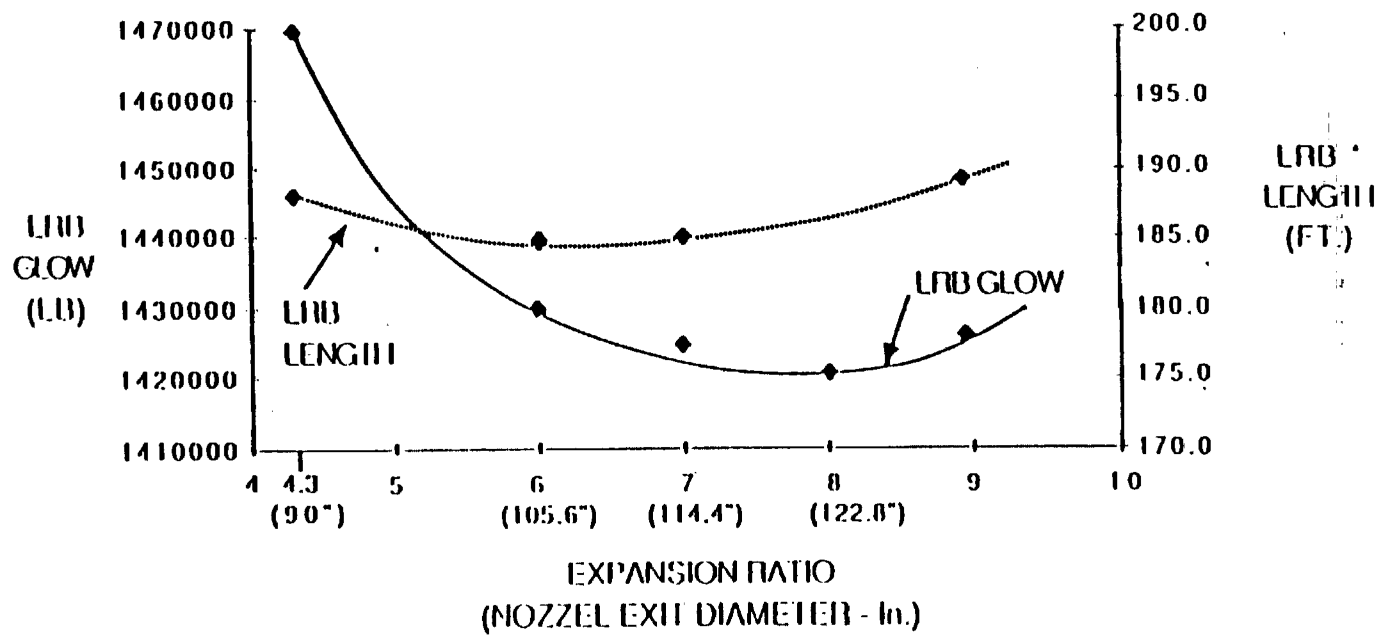



Figure 3.0 - Vehicle Length And Weight Vs. Expansion Ratio For A 4-engine Pressure-fed LO2/RP-1 Booster

* For A 15 Ft. Equivalent Diameter Booster

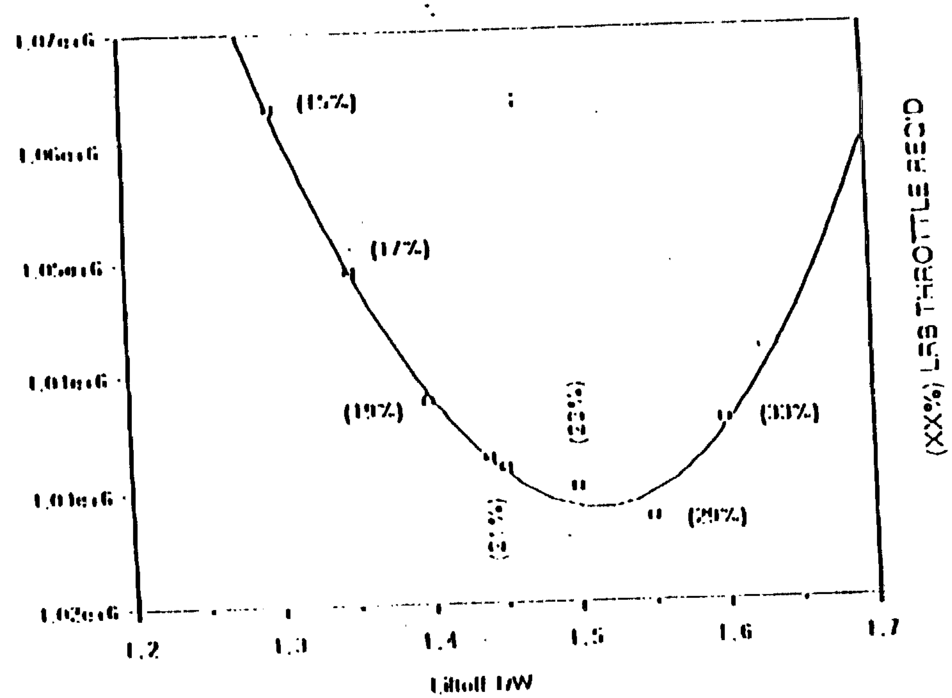



Figure 4.0 - Nominal Liftoff T/W vs. LRB GLOW For a 4 Engine LOX/RP-1 Pump-Fed Configuration

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# TABLE I
## NUMBER OF ENGINES OF COMPARISION

| CRITERIA | 3 ENGINES PER LRB | | 4 ENGINES PER LRB | | 6 ENGINES PER LRB | |
|---|---|---|---|---|---|---|
| | Pump Fed | Pressure Fed | Pump Fed | Pressure Fed | Pump Fed | Pressure Fed |
| SAFETY/RELIABILITY:<br>•Propulsion system<br>(Nominal Mission)<br>(ATO - One Engine-Out) | .9414<br>.9957 | .9650<br>.9980 | .9227<br>.9935 | .9530<br>.9970 | .8864<br>.9884 | .9300<br>.9940 |
| STS COMPATIBILITY:<br>• Complexity (Ground/Flight Operations)<br>• Base Heating (Heat Load To Orbiter Body Flap) | LOWEST<br><br>About 10% Increase In Heat Load Compared To 4 Engine Case, But Still Less Than SRBs | | MEDIUM | | HIGHEST<br><br>About 10% Increase In Heat Load Compared To 4 Engine Case, But Still Less Than SRBs | |
| PERFORMANCE:<br>• Throttlibility<br>(Nominal Mission)<br>(ATO) | -33%<br>+16%<br>(49% Range Req'd) | | -29%<br>-35%<br>(35% Range Req'd) | | -19%<br>-22%<br>(22% Range Req'd) | |
| • Total Engine Weight Per LRB | 21,900 LBs | | 21,300 LBs | | 23,300 LBs | |
| COST<br>• LRB Engine DDT&E Cost<br>• Engines Recurring Cost Per LRB | $1101 M<br>$22.3 M | | $834 M<br>$19.8 M | | $645 M<br>$19.3 M | |

LIQUID ROCKET BOOSTER
TRADE STUDY ERB
JANUARY 27, 1988

TRADE STUDY 1.3
FINAL ERB

# ABORT MODE OPTIMIZATION

STUDY LEADER: JEFF PATTON

SYSTEMS ENGINEER: GREG FARMER

GENERAL DYNAMICS
*Space Systems Division*

# 1.3 ABORT MODE OPTIMIZATION
## Planning Sheet 2

REQUIREMENTS:

- 70 KLB PAYLOAD TO 150 NM ORBIT, 28.5 DEG INCLINATION WITH ORBITER SSME's LIMITED TO 100% THRUST
- 59 KLB PAYLOAD TO 150 NM ORBIT, 28.5 DEG INCLINATION WITH ORBITER SSME's LIMITED TO 104% THRUST
- DESIGN GOAL TO MAKE MISSION (ABORT-TO-ORBIT) WITH ONE LRB ENGINE OUT

CONSTRAINTS:

- USE APPLICABLE SECTIONS FROM THE SHUTTLE OPERATIONAL DATA BOOK (JSC 18934, VOL 1, REV D)
- ONLY STANDARD NOMINAL MECO TARGETS WILL BE CONSIDERED
- NO ORBITER SYSTEM WILL BE IMPACTED BEYOND THE CURRENT, NOMINAL OPERATING LIMITS (ORBITER SSME, OMS LOADING)

# 1.3 ABORT MODE OPTIMIZATION
# Planning Sheet 3

## Assumed Requirements

| NUMBER | REQUIREMENT STATEMENT | CATEGORY | SOURCE |
|---|---|---|---|
| 1. | LRB ENGINES ARE THROTTLED | PROPULSION | GDSS |
| 2. | MECO UNDERSPEED FOR TAL ABORT CAN BE NO GREATER THAN 290 fps | FLIGHT OPS | NASA/JSC |
| 3. | MECO UNDERSPEED FOR AOA OR ATO CAN BE NO GREATER THAN 490 fps | FLIGHT OPS | NASA/JSC |
| 4. | LOWER MECO TARGETS RESULT IN ABORTS IN ALL CASES | FLIGHT OPS | NASA/JSC |
| 5. | TRAJECTORIES VIOLATING CURRENT STS WING LOADING CONSTRAINTS ARE UNACCEPTABLE | ORBITER | NASA/JSC |
| 6. | LRB'S WILL UTILIZE SOME METHOD OF THRUST VECTOR CONTROL | LRB | GDSS |
| 7. | FAST SEPARATION CAPABILITY OF THE ORBITER FROM THE ET/LRB STACK WILL EXIST | ORBITER | GDSS |

# 1.3 ABORT MODE OPTIMIZATION
# Planning Sheet 3 (cont)

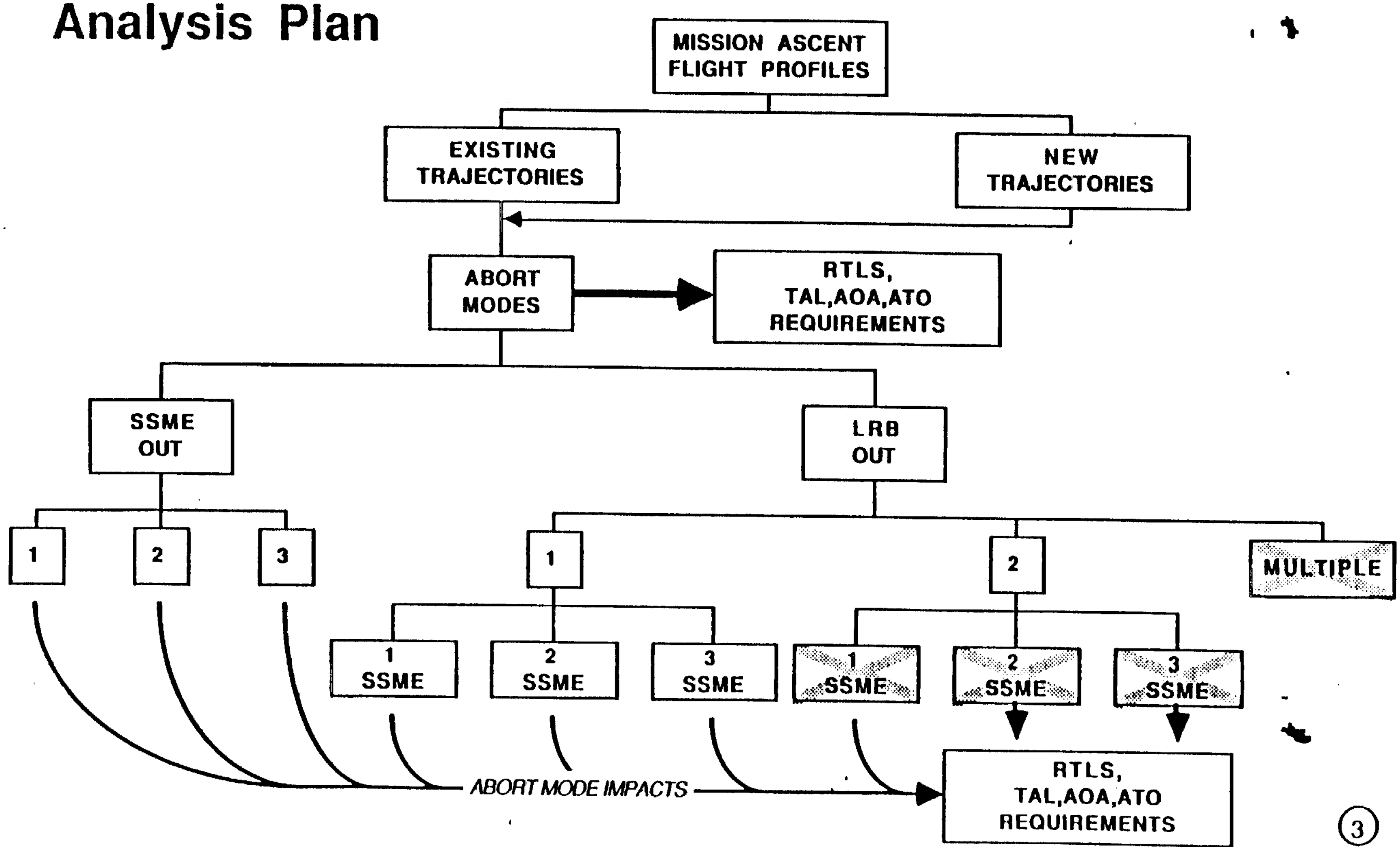
## Assumed Requirements

| NUMBER | REQUIREMENT STATEMENT | CATEGORY | SOURCE |
|---|---|---|---|
| 8. | ORBITER MANUEVERING LIMIT CONTINGENCY ABORTS IS 3.5 G's (Z AXIS) | ORBITER | NASA/JSC |
| 9. | LRB's MAY BE SHUT DOWN AND SAFELY SEPARATED AT 80 SECONDS INTO THE FLIGHT | LRB | GDSS |

55

# 1.3 ABORT MODE OPTIMIZATION
# Planning Sheet 4

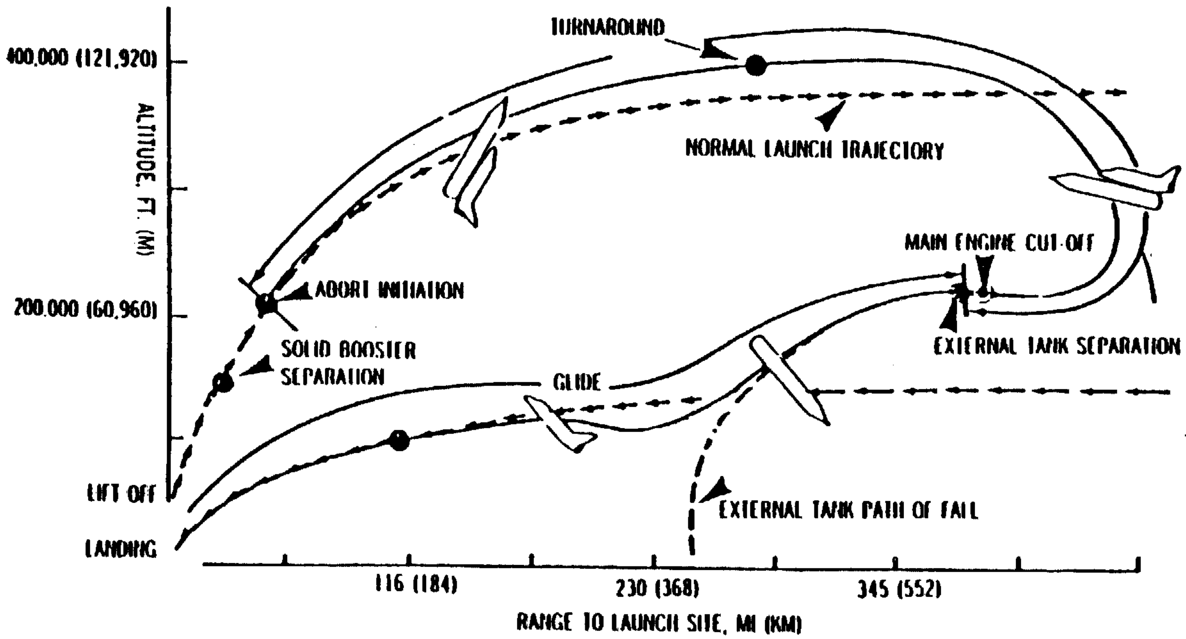
## Analysis Plan



# 1.3 ABORT MODE OPTIMIZATION
## Abort shaping background

- INTACT ABORTS: RETURN TO LAUNCH SITE (RTLS), TRANSATLANTIC ABORT LANDING (TAL), ABORT TO ORBIT (ATO), ABORT ONCE AROUND (AOA)
  - CALLED "INTACT" BECAUSE RECOVERY OF CREW/VEHICLE IS HIGHLY LIKELY AND REPRESENTS RELATIVELY GOOD (?) ABORT MODES
  - TRAJECTORY SHAPING DONE TO OPTIMIZE THESE ABORTS
- CONTINGENCY ABORTS: ABORT ON PAD, SPLIT-S, LOFT-RETURN, OCEAN DITCH (MULTIPLE FAILURES, ie SSMEs+LRBs)
  - CALLED "CONTINGENCY" BECAUSE RECOVERY OF CREW/VEHICLE IS UNLIKELY AND CONDITIONS OCCURING TO WARRANT SUCH AN ABORT ARE DRASTIC (AND UNLIKELY)
  - TRAJECTORY IS NEVER MODIFIED TO IMPROVE THESE ABORTS

# RTLS ABORT SYNOPSIS




DISADVANTAGES OF RTLS

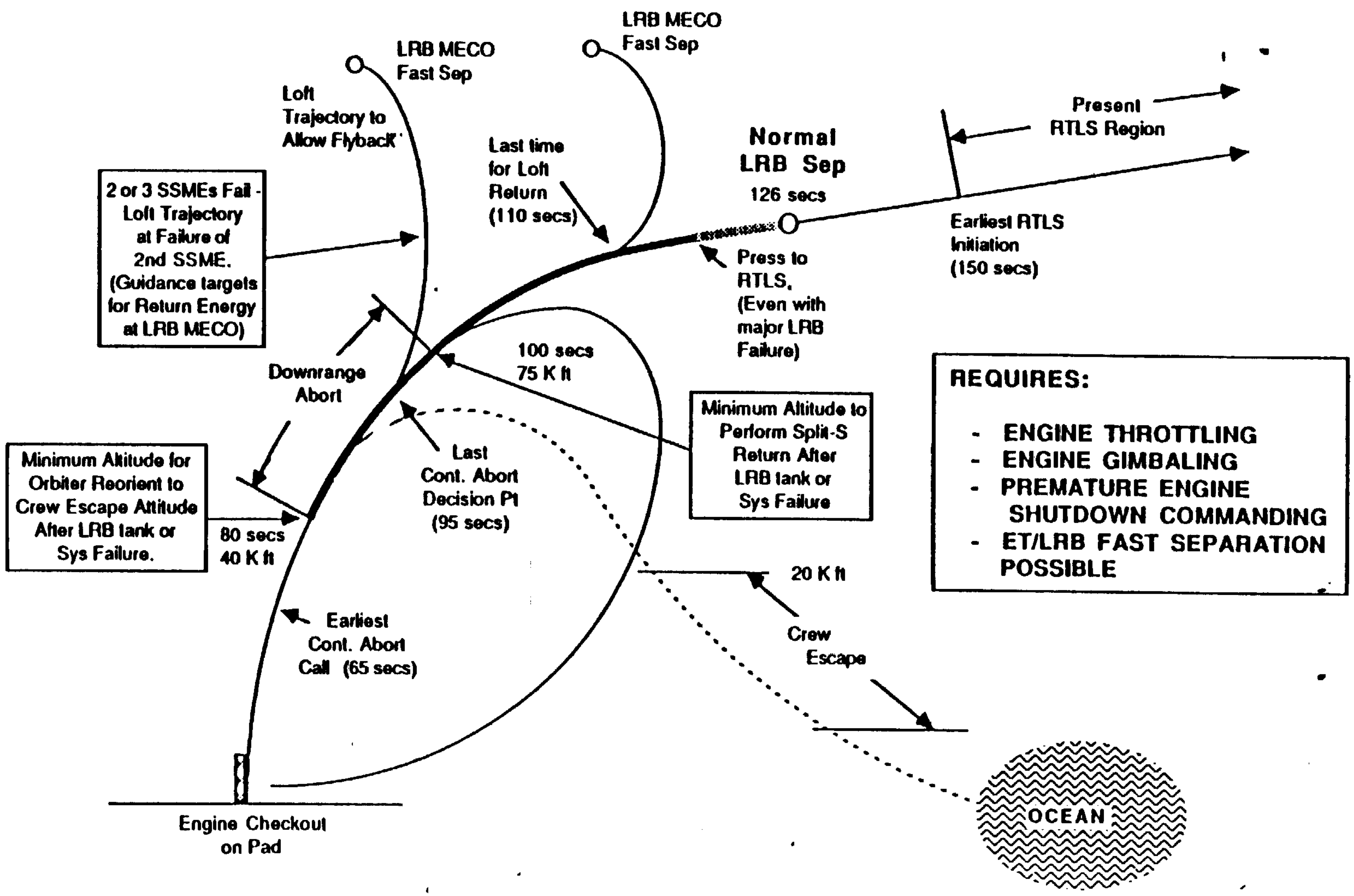
1. RTLS TIME UNTIL LANDING IS LONGER THAN TAL
2. A SECOND FAILURE OF AN ORBITER SSME DURING RTLS RESULTS IN A DITCH, A SECOND ORBITER SSME FAILURE DURING TAL IS TOLERABLE.
3. ORBITER MANEUVERING IS SEVERE (INCLUDING FLYING BACKWARDS INTO ITS OWN PLUME AND A POWERED PITCHDOWN MANEUVER).

ADVANTAGES OF RTLS

1. RETURNS ORBITER TO LAUNCH SITE FOR FAILURES WHERE TAL IS IMPOSSIBLE. (SUCH AS EARLY ORBITER SSME FAILURES)

# FIRST STAGE CONTINGENCY ABORT ANALYSIS

## NEW ABORTS UTILIZING LRB CAPABILITY



# 1.3 ABORT MODE OPTIMIZATION
## Results (Trends)

**VARIOUS METHODS OF TRAJECTORY SHAPING AND VEHICLE SIZING WERE INVESTIGATED TO IMPROVE STS/LRB ABORTS**

- TRAJECTORY SHAPING (LOFTING, DEPRESSING)
  - MAXIMUM DYNAMIC PRESSURE (Q, psf)
  - ANGLE OF ATTACK (ALPHA, deg)
- VEHICLE SIZING
  - THROTTLING REQUIREMENT
  - NUMBER OF ENGINES NECESSARY
  - VARYING THRUST/WEIGHT AT LIFTOFF
  - SIZE TO NOMINAL MISSION OR TO ATO

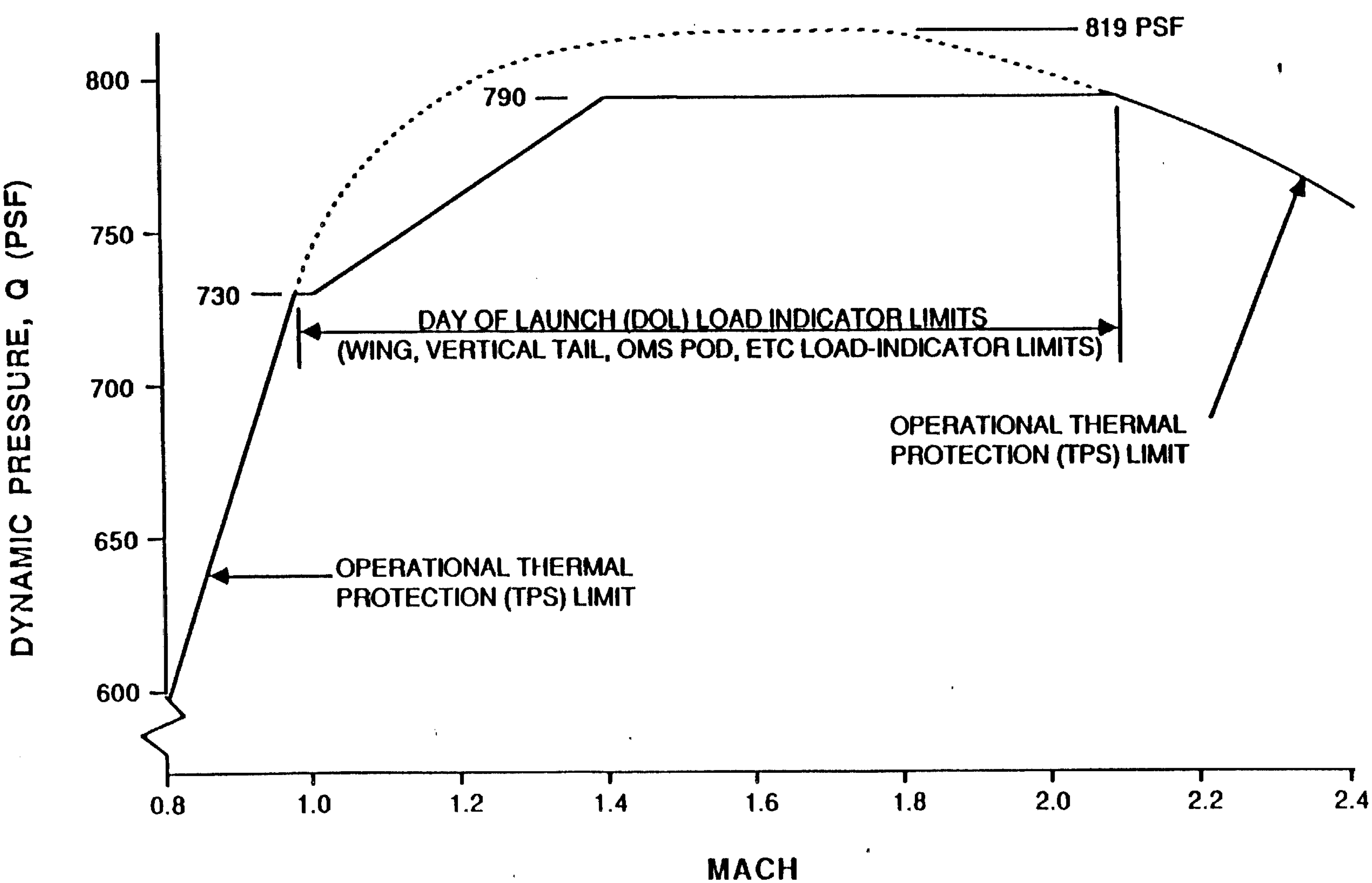
6B

# 1.3 ABORT MODE OPTIMIZATION
## Results (Trends)

TRAJECTORY SHAPING

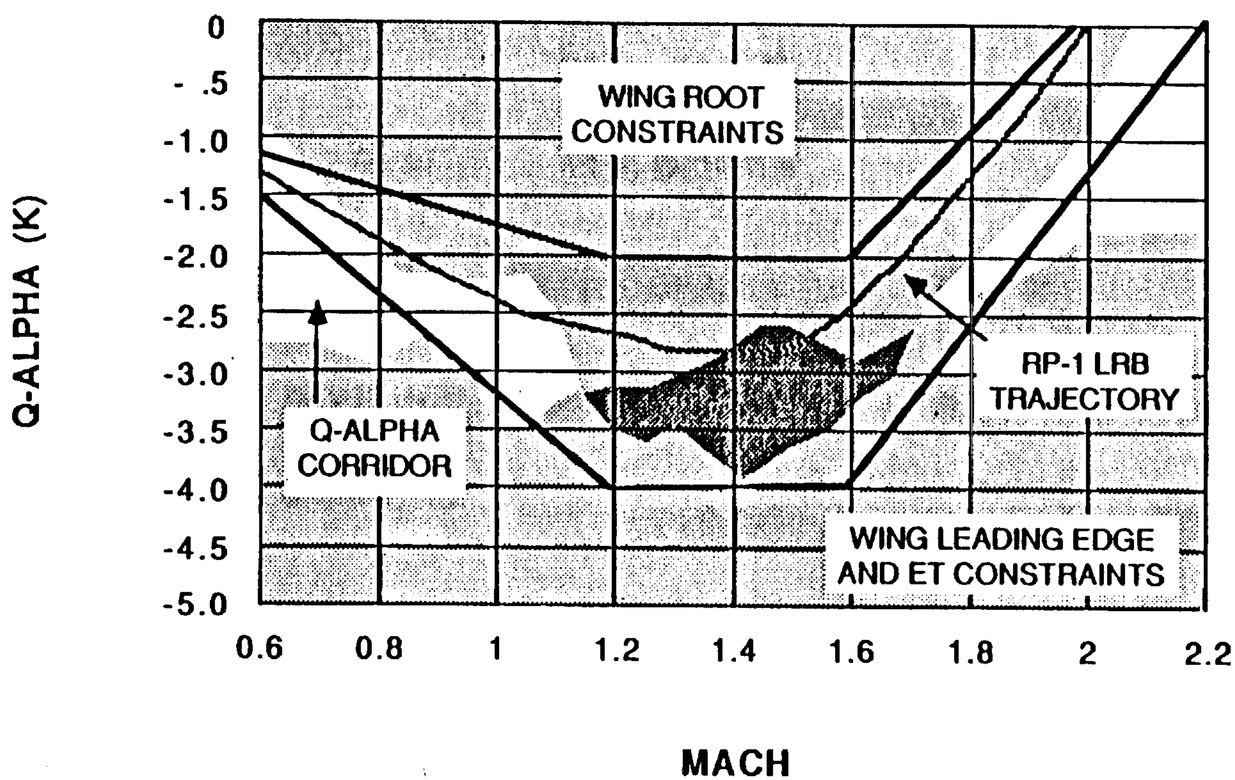
- ONLY 2 CONSTRAINTS ARE ABLE TO BE VARIED DURING ASCENT: Q and ALPHA
  - NASA SPECIFIED QALPHA DURING THE TRANSONIC REGION TO BE -3000 AND ALPHA BETWEEN -4 deg TO -5 deg ("QALPHA CORRIDOR")
  - Q, THEREFORE, CAN VARY BETWEEN 600 psf AND 750 psf
- THESE RESULT FROM CONSTRAINTS USED FOR STS-26, A HIGHLY CONSTRAINED MISSION (MAX Q = 750 psf)
- FUTURE FLIGHTS ARE EXPECTED TO FLY AT LARGER MAX Q's
- THIS ANALYSIS VARIED Q BETWEEN 500 psf AND 800 psf, AND HELD ALPHA TO THE NASA DEFINED LIMITS OF -4 deg TO -5 deg (-2000 < QALPHA < -4000)
  - FLEW THROUGH THE "QALPHA CORRIDOR"

# MAXIMUM DYNAMIC PRESSURE



# Q-ALPHA CORRIDOR

Q NOMINAL = 690



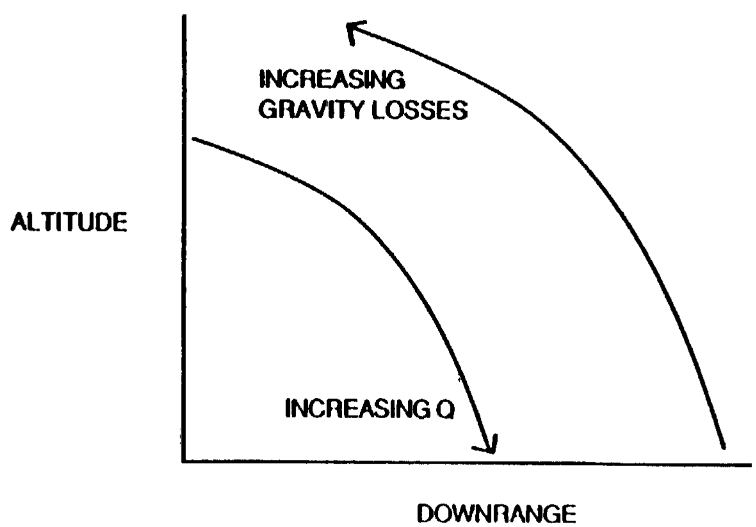
# 1.3 ABORT MODE OPTIMIZATION
## Results (Trends)

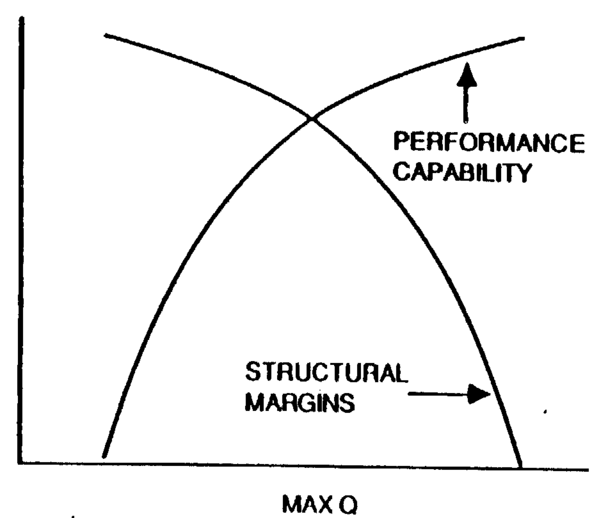
**Q AND GRAVITY LOSSES AS TRAJECTORY/LAUNCH VEHICLE SIZING INDICATORS**

- DECREASING Q REPRESENTS A MORE "LOFTED" TRAJECTORY
- INCREASING GRAVITY LOSSES RESULTS AS THE LAUNCH VEHICLE "FIGHTS" TO OVERCOME GRAVITY

- BOTH ARE CRITICAL TO LAUNCH VEHICLE SIZING/PERFORMANCE DETERMINATIONS

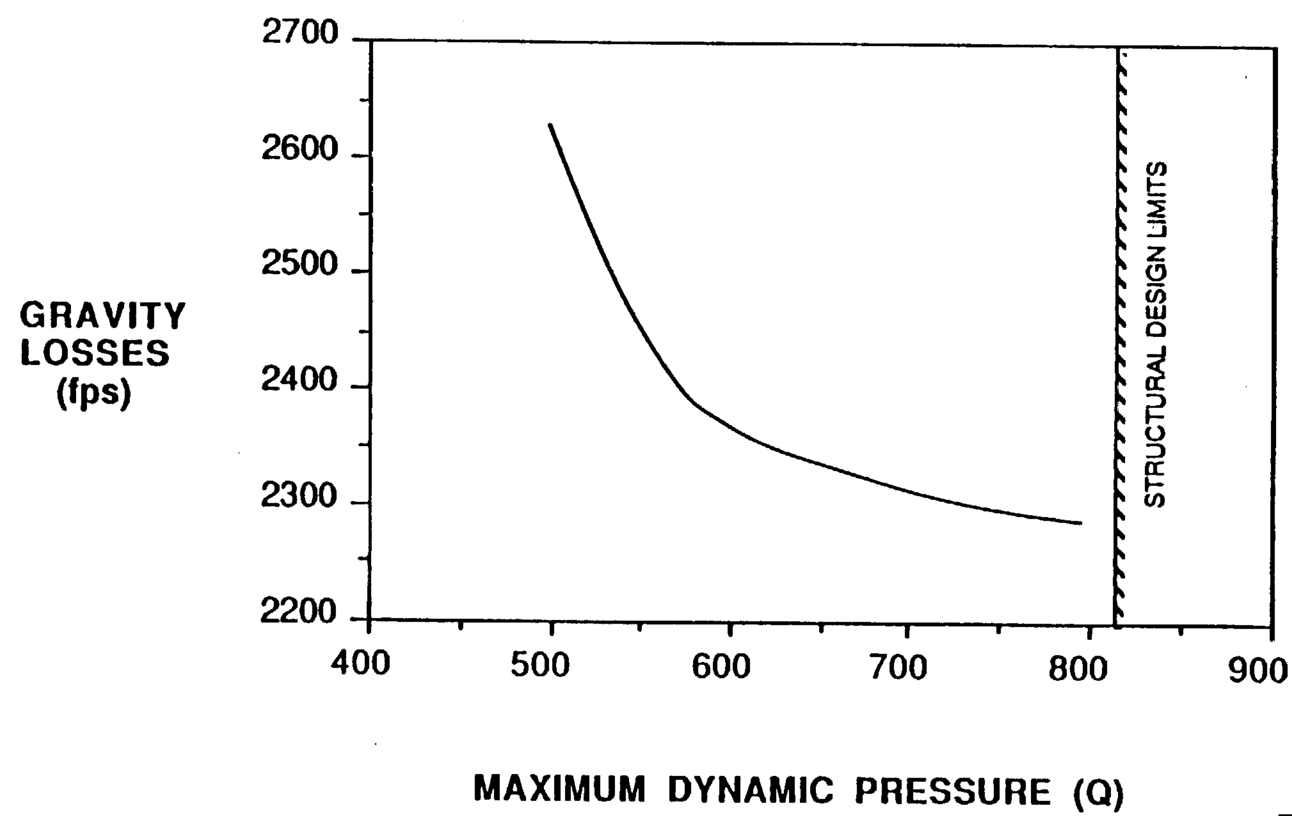




# DYNAMIC PRESSURE vs GRAVITY LOSSES

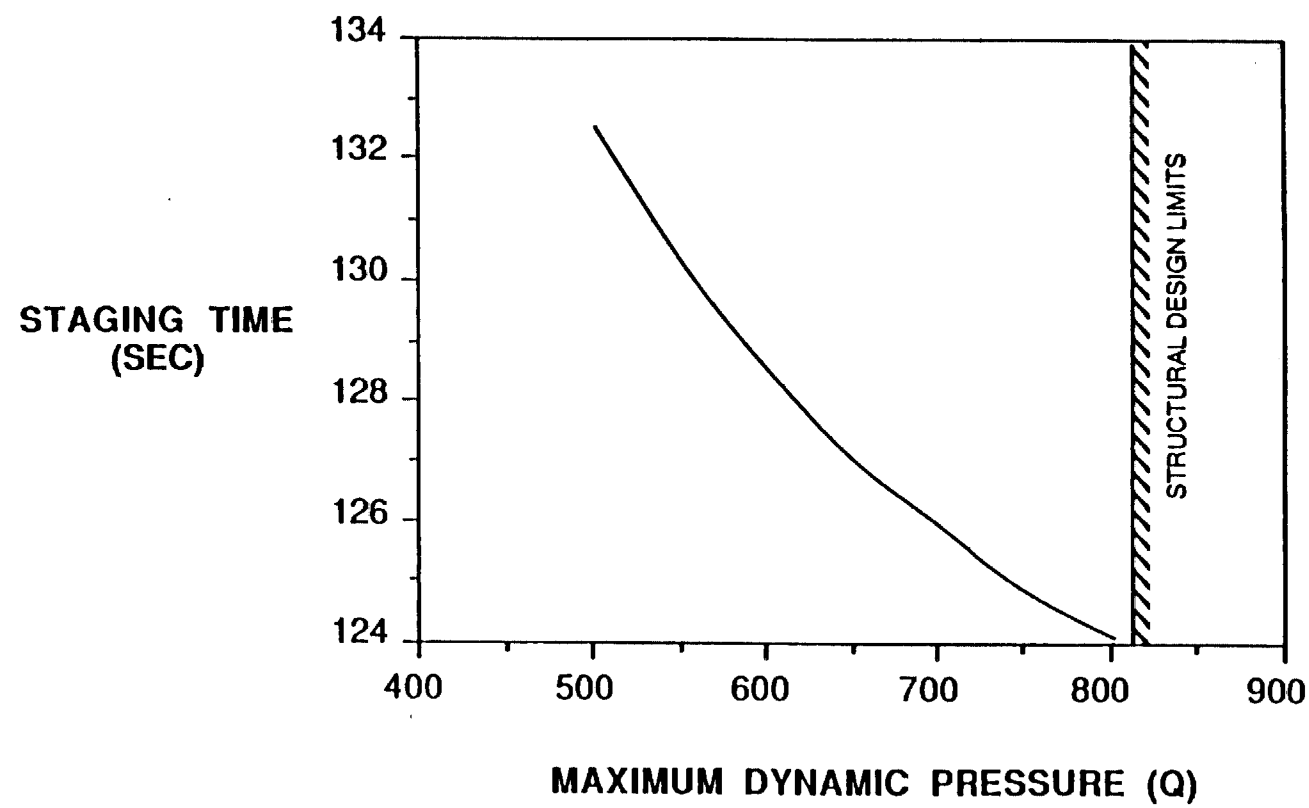
- AS Q DECREASES (LOFTING), GRAVITY LOSSES INCREASE DRAMATICALLY
- RESULTS IN LARGER LRB




5D (RP-1)
4 ENGINES/LRB

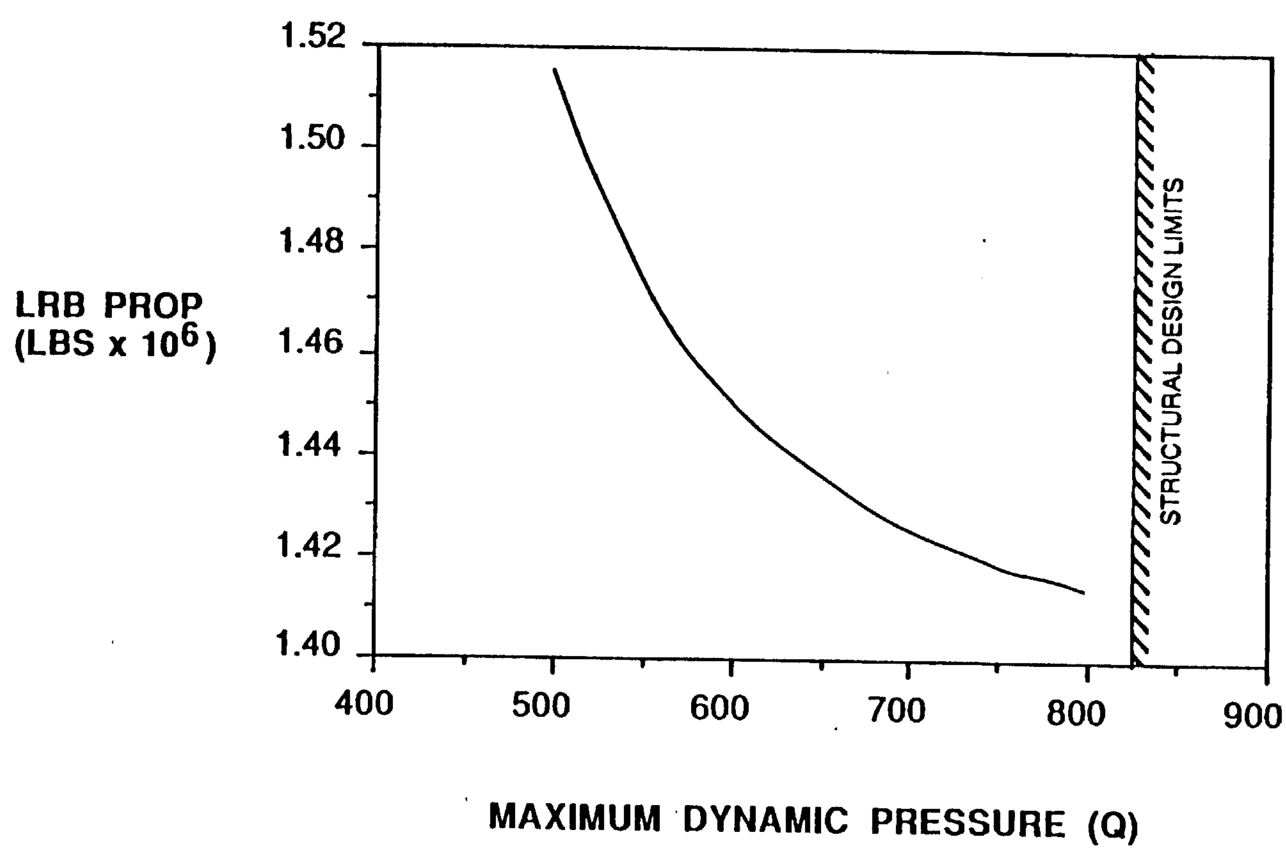
# DYNAMIC PRESSURE vs STAGING TIME

- INCREASED Q (DECREASED GRAVITY LOSSES) RESULT IN SMALLER LRB'S AND EARLIER STAGING TIMES




5D (RP-1)
4 ENGINES/LRB

# DYNAMIC PRESSURE vs LRB PROPELLANT

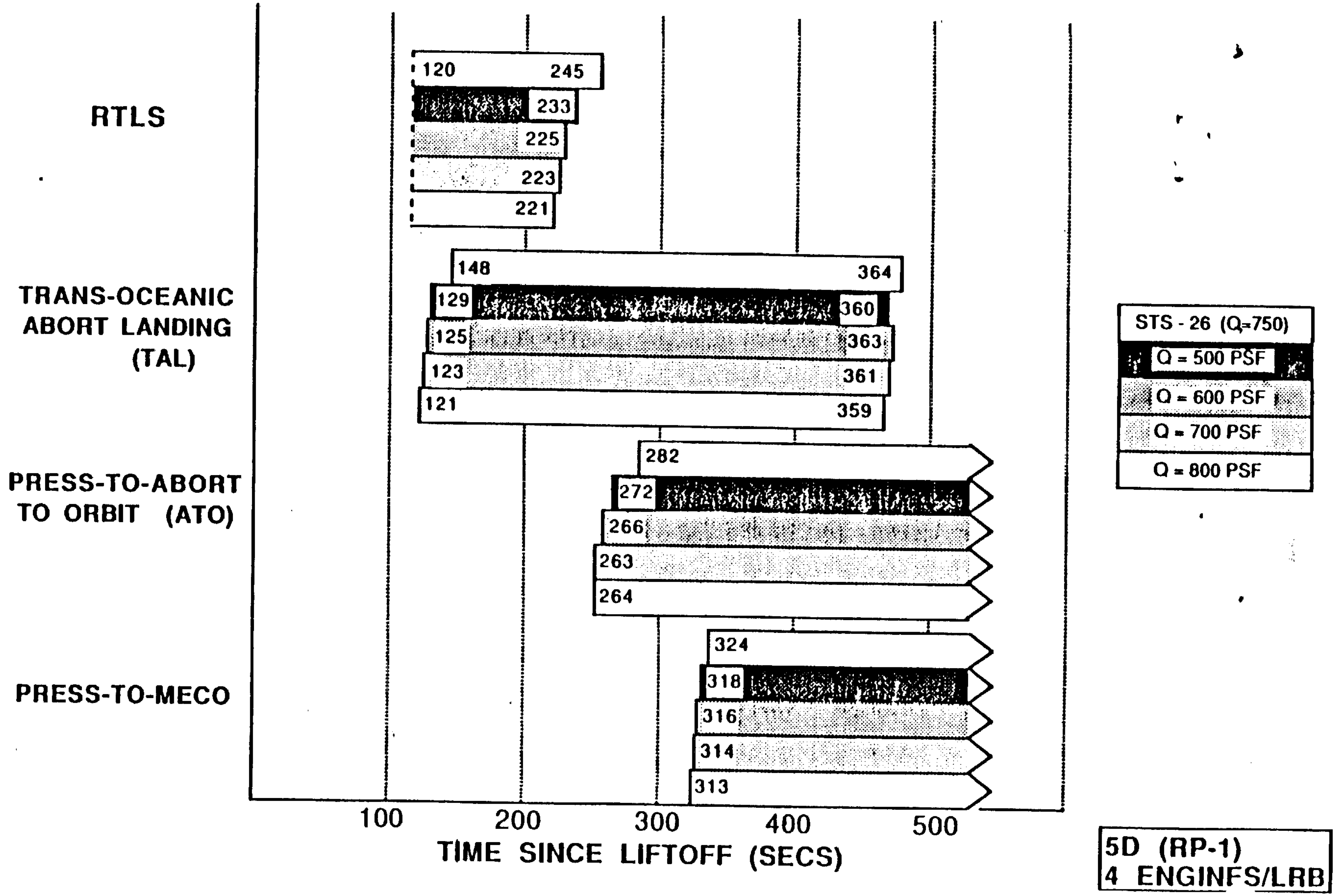



5D (RP-1)
4 ENGINES/LRB

# 1.3 ABORT MODE OPTIMIZATION
## Results (Trends)

- INCREASING Q (DEPRESSED TRAJECTORY) IMPROVES DOWNRANGE ABORTS
  - GAIN VELOCITY QUICKLY
  - ATTAIN INCREASED ENERGY STATE
  - LATER ABORTS REQUIRE MORE ENERGY
- DECREASING Q (LOFTED TRAJECTORY) IMPROVES RTLS ONLY
  - GAIN VELOCITY SLOWER
  - INSUFFICIENT ENERGY FOR DOWNRANGE ABORTS
  - FIRST STAGE CONTINGENCY ABORTS ARE IMPROVED

# Q AFFECTS ON INTACT ABORT BOUNDARIES



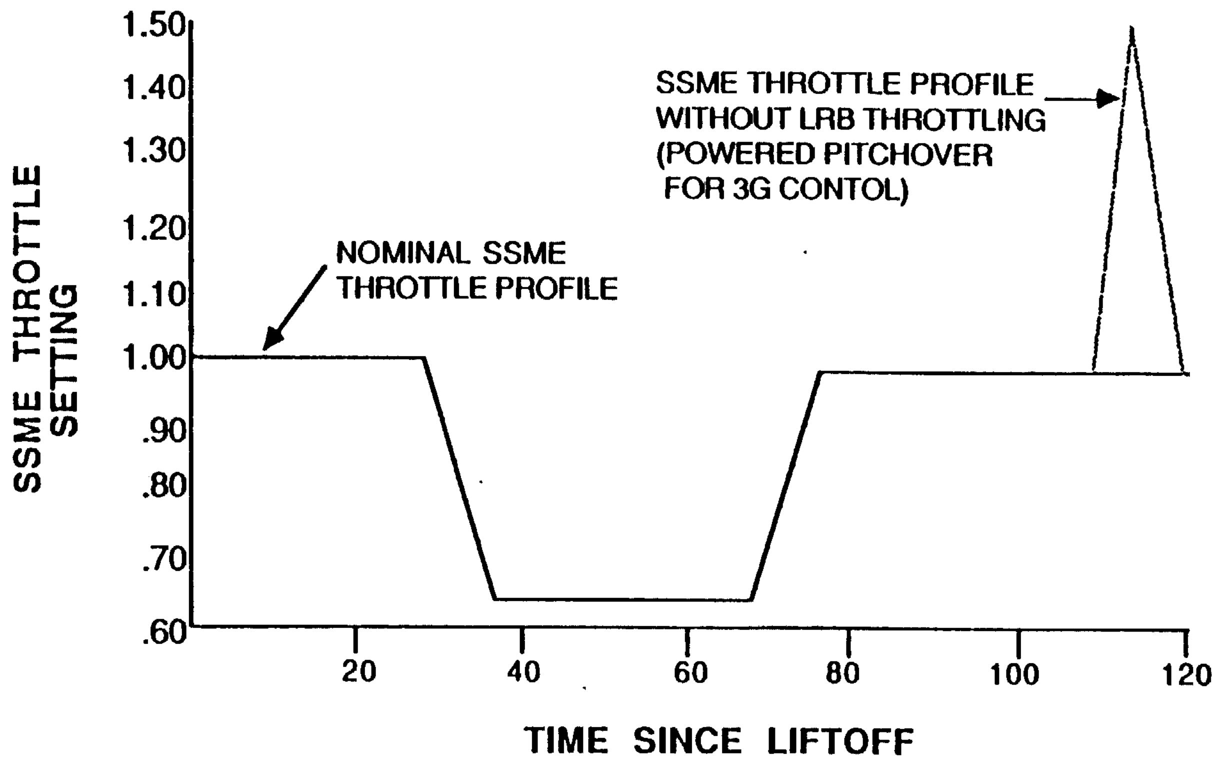
# 1.3 ABORT MODE OPTIMIZATION
## Results (Trends)

RESIZING VEHICLE FOR ABORTS

- THROTTLING REQUIREMENT
- NUMBER OF ENGINES
- VARYING THRUST/WEIGHT AT LIFTOFF
- SIZE VEHICLE FOR NOMINAL MISSION OR ATO?

# 1.3 ABORT MODE OPTIMIZATION
## Results (Trends)

## ARE THE LRB's REQUIRED TO THROTTLE?




- WITHOUT LRB THROTTLING, THE ORBITER SSME'S ARE REQUIRED TO THROTTLE UP 50% AND THE VEHICLE STILL VIOLATES 3G LIMIT

# 1.3 ABORT MODE OPTIMIZATION
Results (Trends)

## NUMBER OF ENGINES

- CURRENT VEHICLES SIZED FOR 4 ENGINES
- ENGINE-OUT REQUIREMENT FOR ATO WILL DETERMINE THROTTLING RANGE REQUIREMENTS
- PROPULSION GROUP INDICATES THAT THE MAXIMUM THROTTLING RANGE FOR THE LRB's IS 100% TO 65%
- TRAJECTORY RUNS INDICATE THAT MAXIMUM RANGE IS REQUIRED (65%) FOR THE 7 (OF 8) ENGINES RUNNING CASE
- RESULTS IN THRUST IMBALANCE DURING FLIGHT, BUT BY CONTROLLED THROTTLING, BOTH LRB's BURN OUT AT THE SAME TIME
- DECREASING TOTAL NUMBER OF ENGINES (5 OF 6) WOULD REQUIRE LARGER THROTTLE RANGE TO MAINTAIN PROPELLANT MANAGEMENT

6B

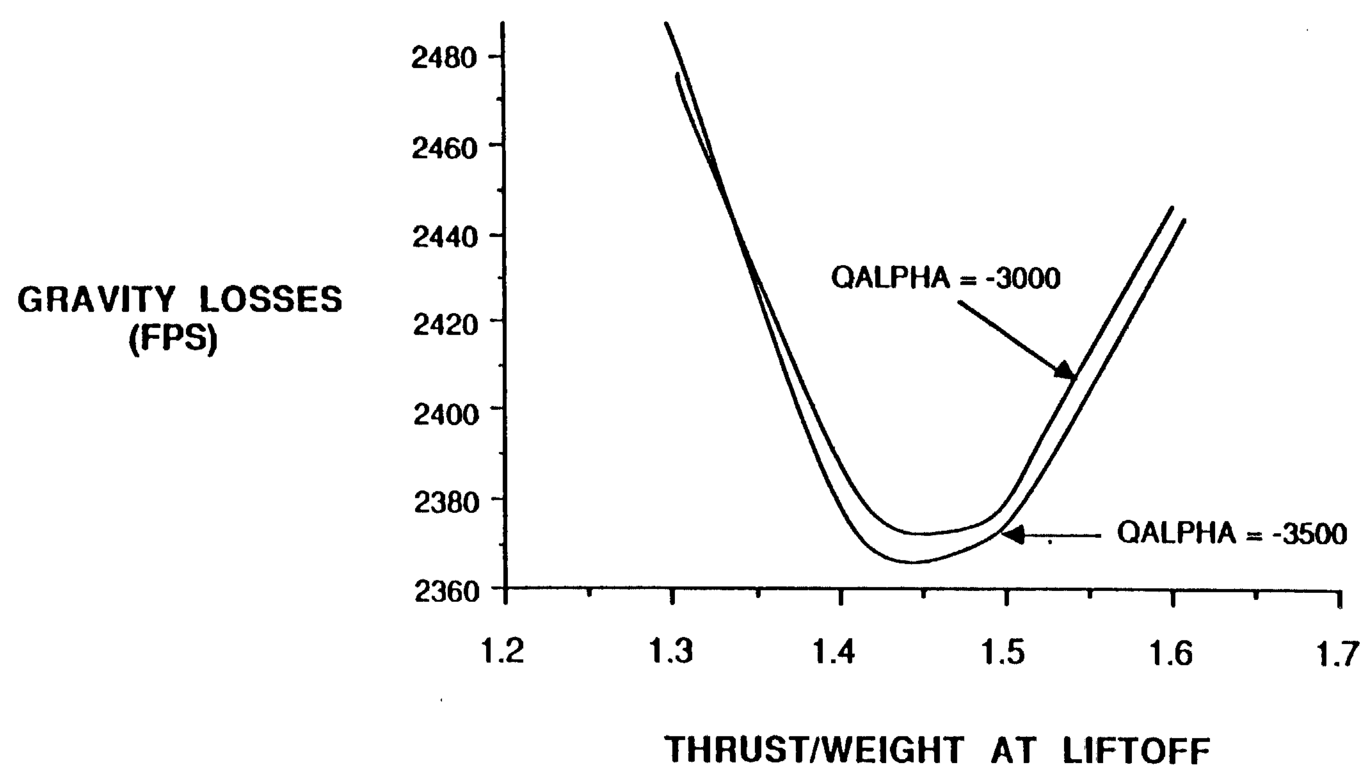
# 1.3 ABORT MODE OPTIMIZATION
## Results (Trends)

VARYING THRUST/WEIGHT AT LIFTOFF

- DETERMINE OPTIMUM T/W AT LIFTOFF
- INVESTIGATE HIGHER/LOWER T/W

# T/W vs GRAVITY LOSSES

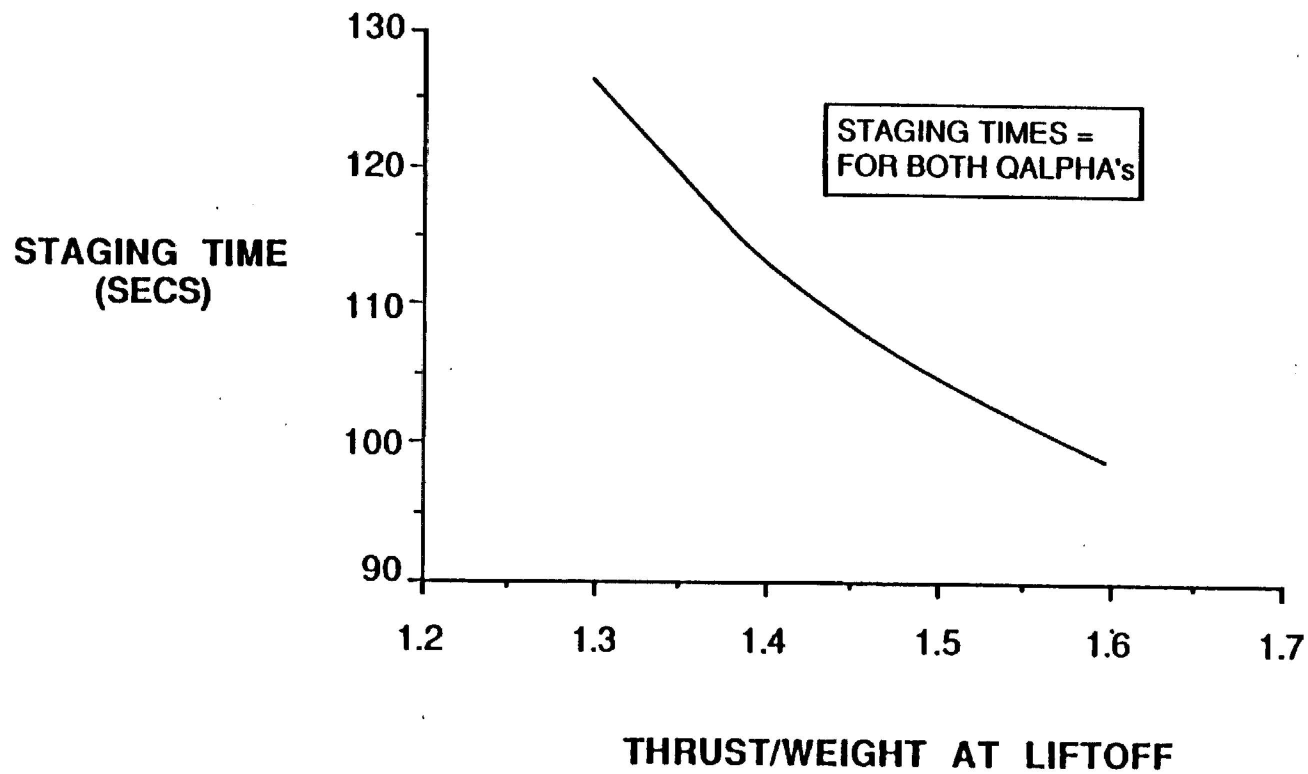
- AS T/W INCREASES, GRAVITY LOSSES DECREASE TO OPTIMIUM T/W
- QALPHA = -3500 HAS LOWER LOSSES = LIGHTER VEHICLE




5D (RP-1)
4 ENGINES/LRB

# NOMINAL T/W AT LIFTOFF vs STAGING TIME

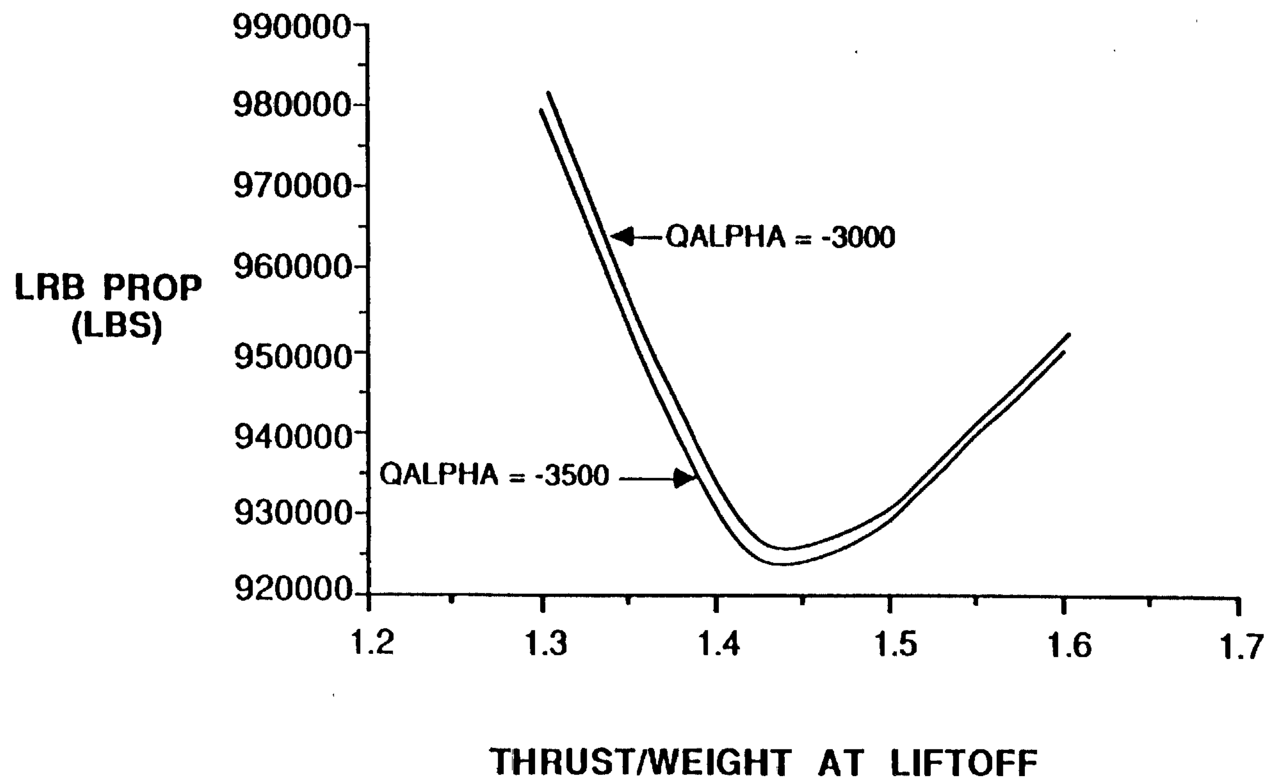
- LARGER BOOSTER (GREATER WEIGHT) BURNS LONGER




5D (RP-1)
4 ENGINES/LRB

# NOMINAL MINIMUM T/W AT LIFTOFF

- LIGHTEST VEHICLE IS AT T/W =1.42, QALPHA = -3500



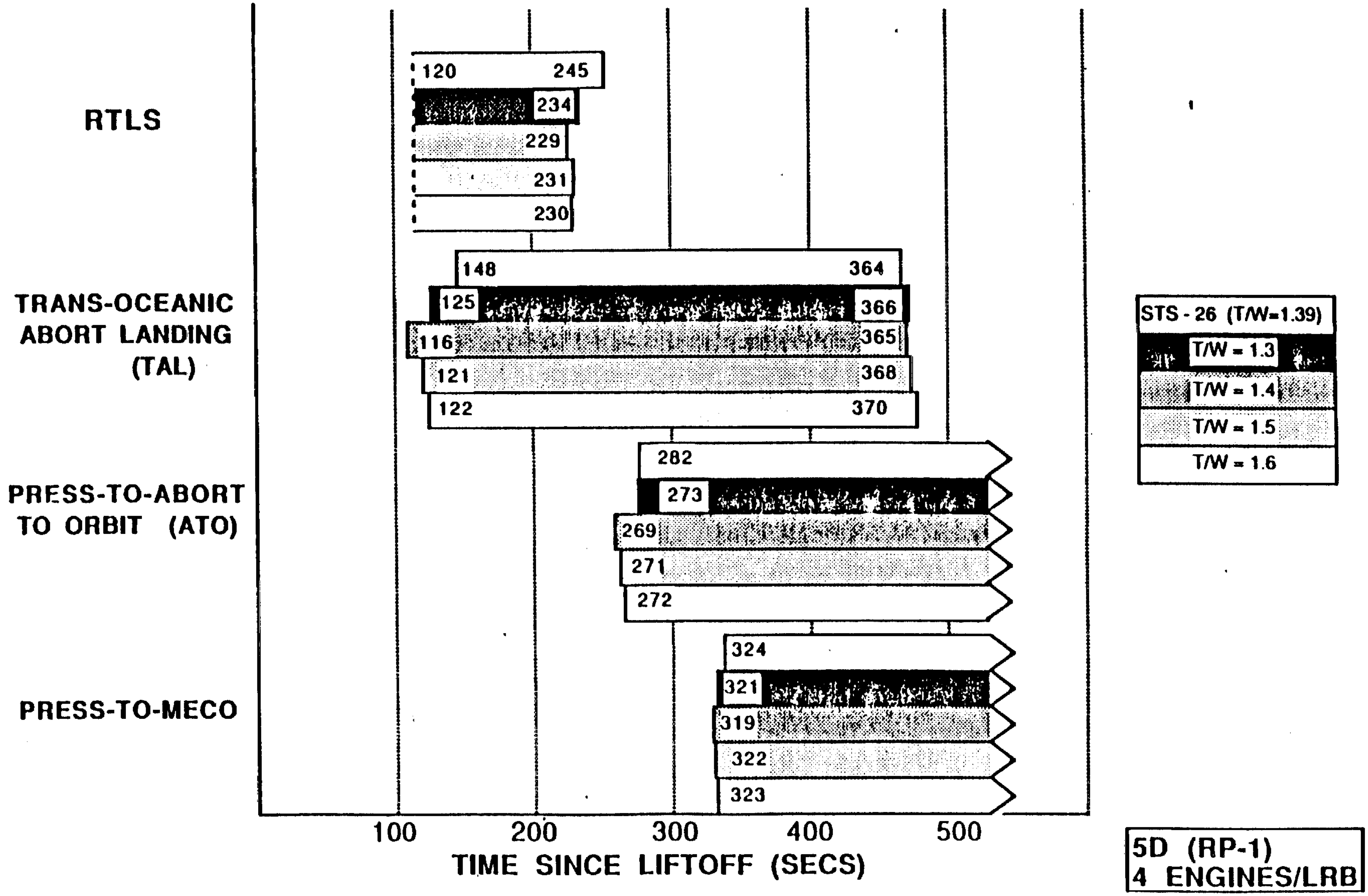

5D (RP-1)
4 ENGINES/LRB

# 1.3 ABORT MODE OPTIMIZATION
## Results (Trends)

- FOR EITHER QALPHA = -3500 OR -3000, T/W = 1.42 PROVIDES BEST ABORT WINDOWS (RP-1 CONFIGURATION)

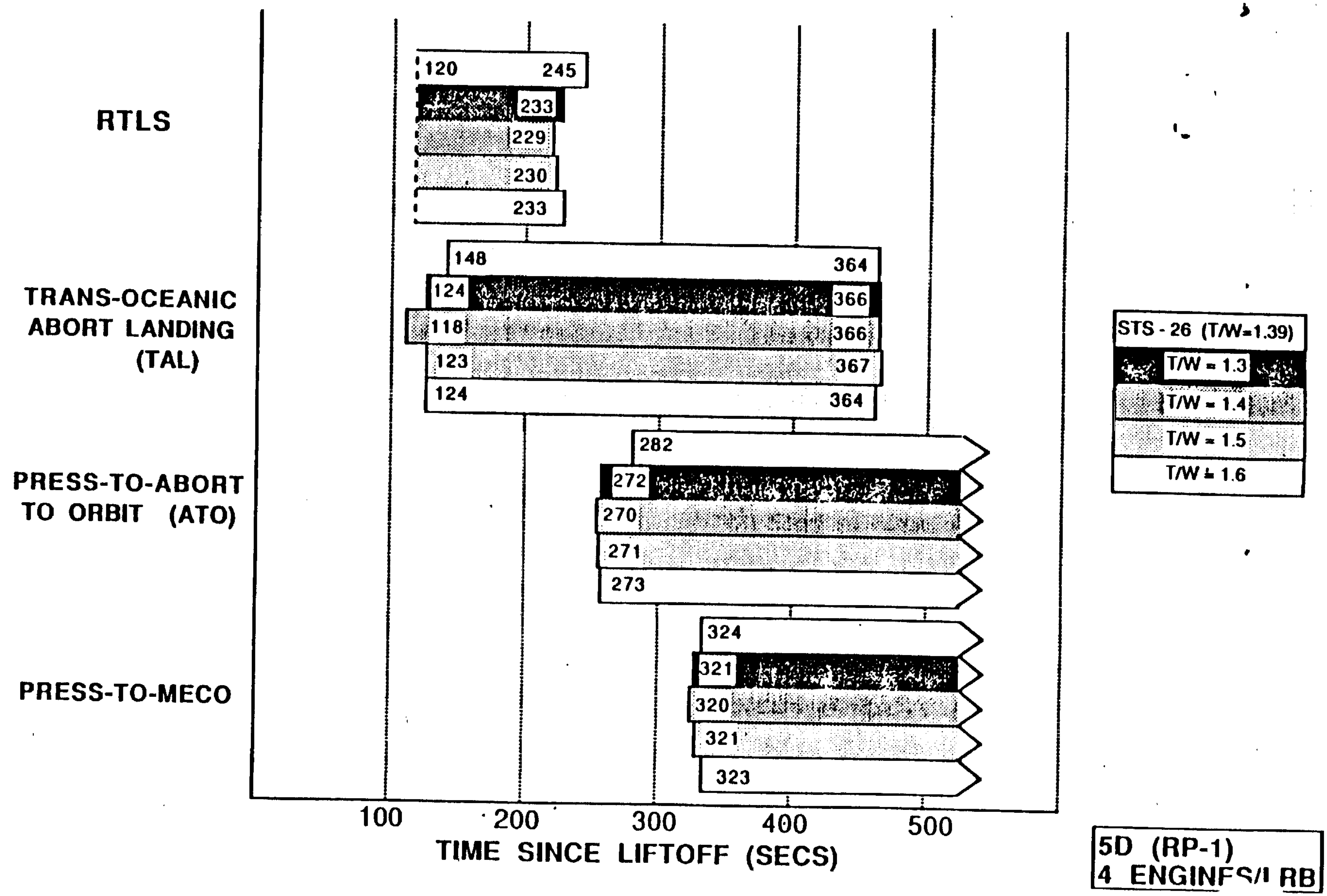
# T/W AFFECTS ON INTACT ABORT BOUNDARIES

QALPHA = -3000



# T/W AFFECTS ON INTACT ABORT BOUNDARIES

QALPHA = -3500



# 1.3 ABORT MODE OPTIMIZATION
## Results (Trends)

### VEHICLE SIZING TO POSSIBLE ORBITS

| | 150 X 150 NMI NOMINAL MISSION 8 ENGINES OPERATING | 105 X 105 NMI ABORT-TO-ORBIT 7 ENGINES OPERATING | 150 X 150 NMI NOMINAL MISSION 7 ENGINES OPERATING |
|---|---|---|---|
| LRB PROPRLLANT PER BOOSTER (LBS) | 940,000 | 910,000 | 1,187,000 |

- NOMINAL MISSION WITH 8 ENGINES OPERATING SIZES VEHICLE OVER ATO MISSION
- VEHICLE SIZE PENALTY OF 33% FOR LRB ENGINE-OUT NOMINAL MISSION

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# 1.3 ABORT MODE OPTIMIZATION
## Derived Requirements List

| NUMBER | REQUIREMENT STATEMENT | CATEGORY |
|---|---|---|
| 1. | RP-1 LRB's WILL NOMINALLY LIFT OFF AT T/W ≈ 1.42 | LRB |
| 2. | LRB SEPARATION SYSTEM MUST BE ABLE TO PROVIDE SAFE SEPARATION WITH PARTIAL LRB PROPELLANT LOAD | LRB |
| 3. | LRB ENGINES MUST BE ABLE TO BE SHUTDOWN PREMATURELY | LRB |
| 4. | ALL LRB CONFIGURATIONS WILL ALLOW FOR SAFE SEPARATION AND FIRST STAGE CONTINGENCY ABORTS | LRB |
| 5. | FOR LRB CONFIGURATIONS WITH LESS THAN 4 ENGINES PER BOOSTER, THROTTLE RANGE MUST EXCEED CURRENT LIMITS (100% - 65%) | LRB |
| 6. | GIMBALLING FOR ENGINE-OUT (LRB OR SSME) | LRB |

# 1.3 ABORT MODE OPTIMIZATION
## Summary of Results

CONCLUSIONS:

- DECREASING DESIGN QALPHA TO -3500 psf IMPROVES DOWNRANGE ABORTS
- LRB ENGINE-OUT IS AN ATTAINABLE GOAL FOR ALL CONFIGURATIONS (F-1 CONFIGURATION IS TO BE DETERMINED)
- LRB's IMPROVE ALL ABORT MODES INCLUDING NEW FIRST STAGE CONTINGENCY ABORTS
  - ABORT-ON-PAD
  - SPLIT-S
  - DOWNRANGE ABORT
  - LOFT RETURN
- TRAJECTORY SHAPING DOES NOT HELP LOFTING FOR FIRST STAGE CONTINGENCY ABORTS

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RECOMMENDATIONS

- WITH NASA APPROVAL, DECREASE QALPHA TO -3500 psf
- CONTINUE ASSESSMENT OF ABORTS INCLUDING:
  - PROPELLANT MANAGEMENT OF LRB's WITH ONE ENGINE-OUT
  - INVESTIGATE IMPROVEMENTS TO SSME FAILURE ABORT WINDOWS UTILIZING LRB THROTTLING

UPDATE ON T.S. 1.3 ABORT

The number one objective of the LRB program is to improve Shuttle safety including better abort capabilities. Obviously this is closely integrated with Orbiter capabilities, so we had many discussions in Houston (such as those on 2/16 - 2/18 1987 per attached itinerary).

Two initial desires were not reasonable:

a) To eliminate the TAL bases by having RTLS and ATO overlap. (Sites still needed for emergencies.)

b) Major trajectory reshaping (lofted or depressed) to improve TAL and ATO. (Orbiter constraints limit trajectory shaping to a large degree.)

Instead we found that improvements in various abort scenarios were all that is reasonable in view of the tight Q-alpha corridor constraints. Engine out and engine throttling abilities are major improvements. Another benefit would result from LRB capability to shut off and separate at about 80 seconds if a splashdown is the last resort.

Continuing trajectory optimizations have shown that each concept has an optimum launch T/W. This trade study shows optimum T/W = 1.42 for LOX/RP-1. Later analyses to optimize gross weight showed 1.5 nominal (which allows ATO with 1 engine out).

Other later ideas include throttling up ~ 10% on the side with engine out and down ~80% on the other side.

This work must continue with ever increasing detailed trajectory work by JSC and its contractors.

(Attachment A)

# NASA/JSC TRIP ITINERARY
# (2-16-87 to 2-18-87)

Wednesday, February 17,1988
Session 1
8:30 am - 11:00 am
EAGLE ENGINEERING

| Subject | EAGLE | GDSS |
|---|---|---|
| Abort Mode Design | J. Wood | J. Patton |
| Premature LRB SEP vs FASTSEP | T. Zack | S. Seus |
| Abort Mode Propellant Margins | | W. Thompson |
| Ignition Sequence/Structural Dynamics | W.Hoyler | G. Buchanan |

Session 2
12:30 pm - 4:00 pm
LOCKHEED

| Subject | LOCKHEED | GDSS |
|---|---|---|
| Intact Abort Design | P. Fardelos | J. Patton |
| Contingency Abort Design | D. Blumentrit | S. Seus |
| Premature LRB SEP vs FASTSEP Performance Requirements | | W. Thompson |
| Ignition Sequence/Structural Dynamics | TBD | G. Buchanan |

Thursday, February 18, 1987
Session 3
8:00 am - 11:30 am
NASA/JSC

| Subject | NASA/JSC | GDSS |
|---|---|---|
| RTLS and TAL Abort Design | 1st Lt J. Turner | J. Patton<br>S. Seus |
| Abort Propellant Margins | C. Sparks | W. Thompson |
| Abort Contollability Requirements | C. Frayley | |
| Ignition Sequence/Structural Dynamics | TBD | G. Buchanan |

(Attachment B)

# MEETING ATTENDEES

General Dynamics
Space Systems Division

Steve Seus
Jeff Patton
Walter Thompson
Guy Buchanan
Celeste Salvaggio

Eagle Engineering

Jim Wood
Tom Howe
Carol Blaknoll
Tom Zackrewski
Wil Hoyler

Lockheed Engineering
MaintenanceSupport Company

Jim McCurry
Pete Fardelos
David Blumentrit
Chris Christofferson
Nancy Carter
Wes Kelly

Rockwell Shuttle Operations
Company

Andy Flottorp
Elmer Johnson
Carson Sparks

NASA/JSC

1st Lt. John Turner
Jim Akkerman

LIQUID ROCKET BOOSTER
TRADE STUDY ERB
DECEMBER 4, 1987

TRADE STUDY 1.5
FINAL ERB

# PUMP FED - PROPELLANT SELECTION

STUDY LEADER: TINA NGUYEN

SYSTEMS ENGINEER: MIKE VACCARO

**GENERAL DYNAMICS**
*Space Systems Division*

# 1.5 PUMP FED - PROPELLANT SELECTION
## Planning Sheet 1

### OBJECTIVE:

SELECT THE BEST PROPELLANT COMBINATIONS FOR THREE LIQUID ROCKET BOOSTER CONCEPTS:

- EXPENDABLE WITH NEW ENGINES
- REUSABLE WITH NEW ENGINES
- EXPENDABLE WITH EXISTING ENGINES
- REUSABLE WITH EXISTING ENGINES

### GROUNDRULES/ASSUMPTIONS:

CONFIGURATION = CONVENTIONAL CYLINDRICAL (CURRENT SRB)

VEHICLE L/D RATIO = 12.3

NUMBER OF ENGINES = 4

TANK MATERIAL = AL-LI (WEIGHT OF TANK BASED ON LOAD CONSIDERATION)

FOR NEW ENGINES:

EXIT DIAMETER = 50" (NO MODIFICATIONS IN MLP OR FLAME TRENCH)

= OPTIMIZED NOZZLE FOR 6 PSIA BACK PRESSURE (NO MODIFICATIONS TO FLAME TRENCH)

CHAMBER PRESSURE = BASED ON STBE NORMAL POWER LEVEL

MIXTURE RATIO = BASED ON STBE STUDY

ENGINE CYCLE = GAS GENERATOR

# 1.5 PUMP FED - PROPELLANT SELECTION
## Planning Sheet 2

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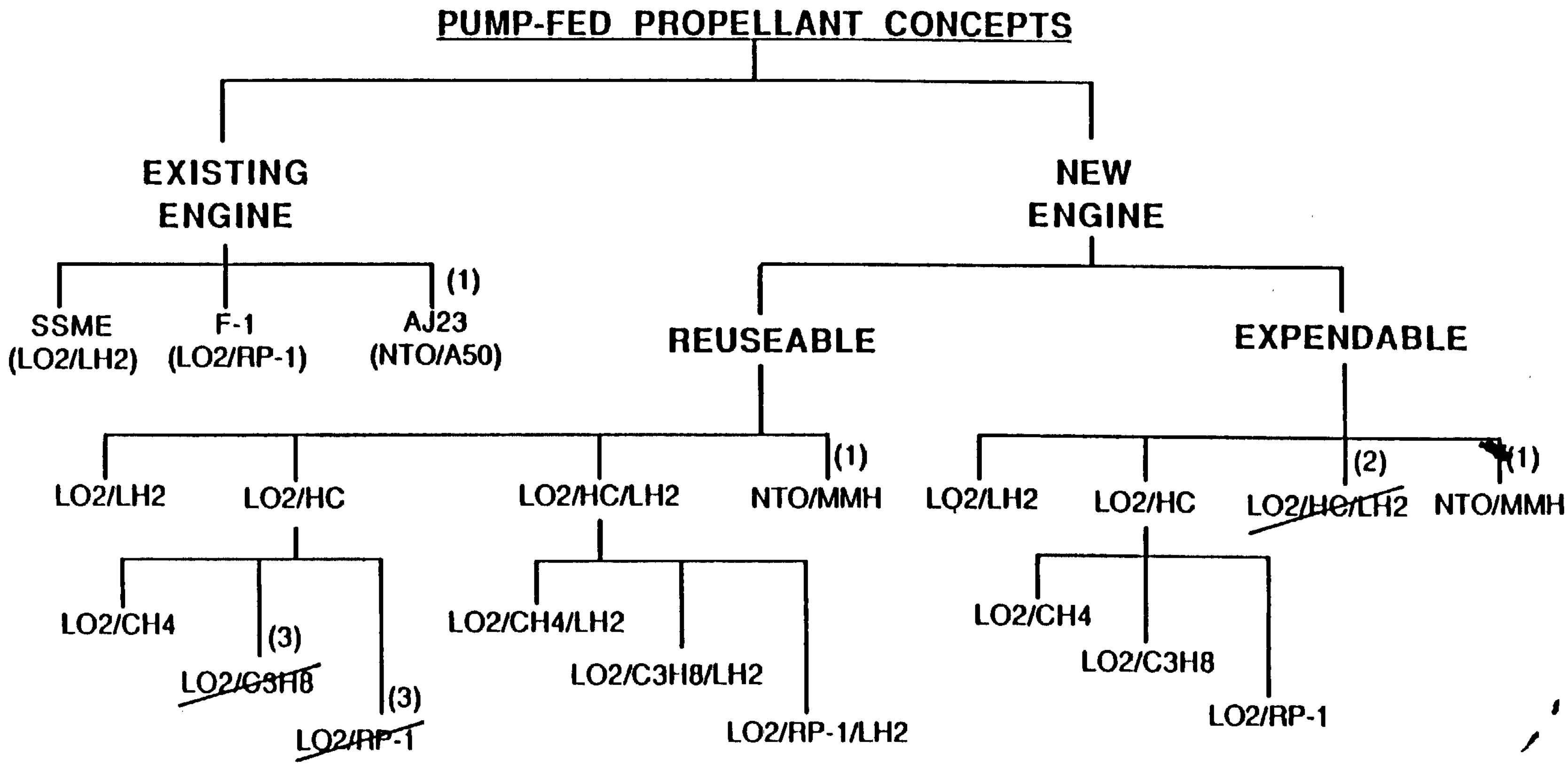
**REQUIREMENTS:**

1. 70 KLB PAYLOAD TO 150 NM ORBIT, 28.5 DEG INCLINATION, WITH ORBITER SSME'S LIMITED TO 100% PL
2. 59 KLB PAYLOAD TO 150 NM ORBIT, 28.5 DEG INCLINATION, WITH ORBITER SSME'S LIMITED TO 104% PL
3. SATISFY STS TRAJECTORY CONSTRAINTS (MAX Q, LIFTOFF T/W, MAX G, ETC.)

**CONSTRAINTS:**

- IMPROVE SAFETY, RELIABILITY AND ENVIRONMENTAL ACCEPTABILITY
- MINIMIZE IMPACT/CHANGES ON ET, ORBITER, LAUNCH SITE AND GSE
- MINIMIZE IMPACTS TO FLAMETRENCH - MAXIMUM De IS LIMITED TO 90in
- MINIMIZE IMPACTS TO MLP - MAXIMIUM De IS LIMITED TO 50in

# 1.5 PUMP FED - PROPELLANT SELECTION
## Planning Sheet 4
## Trade Tree



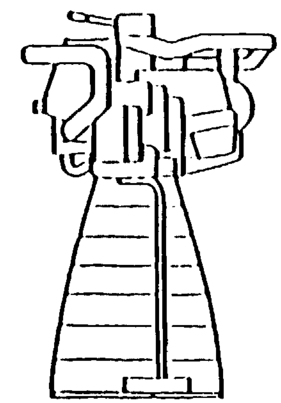

(1) MAY BE ELIMINATED EARLY IN TRADE DUE TO SAFETY & ENVIRONMENTAL IMPACT
(2) NOT VIABLE FOR EXPENDABLE CONCEPT DUE TO HIGH COST
(3) NOT VIABLE FOR REUSABLE CONCEPT DUE TO HIGH COKING PROBLEM

# EXISTING ENGINE EVALUATION

- **ENGINES ANALYZED**
  - SSME - 35
  - F - 1
  - AJ - 23

- **EVALUATION CRITERIA**
  - ENGINE OUT CAPABILITY
  - COST
  - STS COMPATIBILITY (AIRBORNE & GROUND EQUIPMENT)
  - SAFETY
  - AVAILABILITY

# SSME - 35 (LO2/LH2; 4 ENGINES/BOOSTER)



## ADVANTAGES

- ENGINE OUT CAPABILITY - POSSIBLE
- STS COMPATIBILITY (GROUND) - NO FLAME TRENCH IMPACT
- SAFETY - HIGHLY RELIABLE; NOT AS HAZARDOUS AS HYPERGOLS
- AVAILABILITY - CURRENTLY IN PRODUCTION

## DISADVANTAGES

- STS COMPATIBILITY (AIRBORNE) - LARGEST BOOSTER (L = 190': D = 15.4')
- COST - EXPENSIVE ENGINES; HIGHEST MAINTENCE COST; LONGEST TURN-AROUND TIME

# F - 1 (LO2/RP-1; 2 ENGINES/BOOSTER)

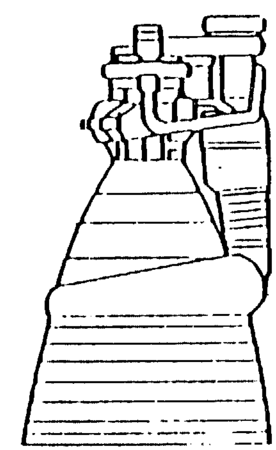
## ADVANTAGES

- STS COMPATIBILITY (GROUND) - NO FLAME TRENCH IMPACT
- STS COMPATIBILITY (AIRBORNE) - MUCH SMALLER BOOSTER THAN SSME - 35
- SAFETY - HIGHLY RELIABLE; NOT AS HAZARDOUS AS HYPERGOLS



## DISADVANTAGES

- AVAILABILITY - PRODUCTION LINE DEACTIVATED
- ENGINE OUT CAPABILITY - IN CONSIDERATION

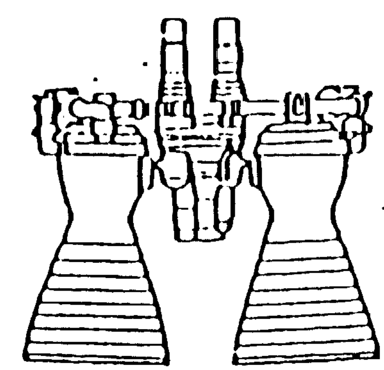


# AJ - 23 (NTO/MMH; 5 SETS OF ENGINES/BOOSTER)

## ADVANTAGES

93

- ENGINE OUT CAPABILITY - POSSIBLE
- STS COMPATIBILITY (GROUND) - NO FLAME TRENCH IMPACT
- STS COMPATIBILITY (AIRBORNE) - SMALLEST BOOSTER SIZE
- AVAILABILITY - CURRENTLY IN PRODUCTION
- COST - LESS EXPENSIVE THAN SSME - 35



## DISADVANTAGES

- SAFETY - HIGHLY TOXIC PROPELLANT

# EXISTING ENGINE TRADE
## Summary

- AJ -23 ENGINES APPEAR TO BE THE LEAST DESIREABLE OPTION DUE TO ENVIRONMENTAL & SAFETY CONSIDERATIONS

- SSME - 35 ENGINES APPEAR TO BE THE MOST DESIREABLE OPTION IF THE LARGE BOOSTER SIZE DOES NOT PROHIBIT INTEGRATION TO THE STS

- F - 1 ENGINES APPEAR TO BE THE PREFERRED OPTION IF THE SSME - 35 CANNOT BE INTEGRATED WITH THE STS

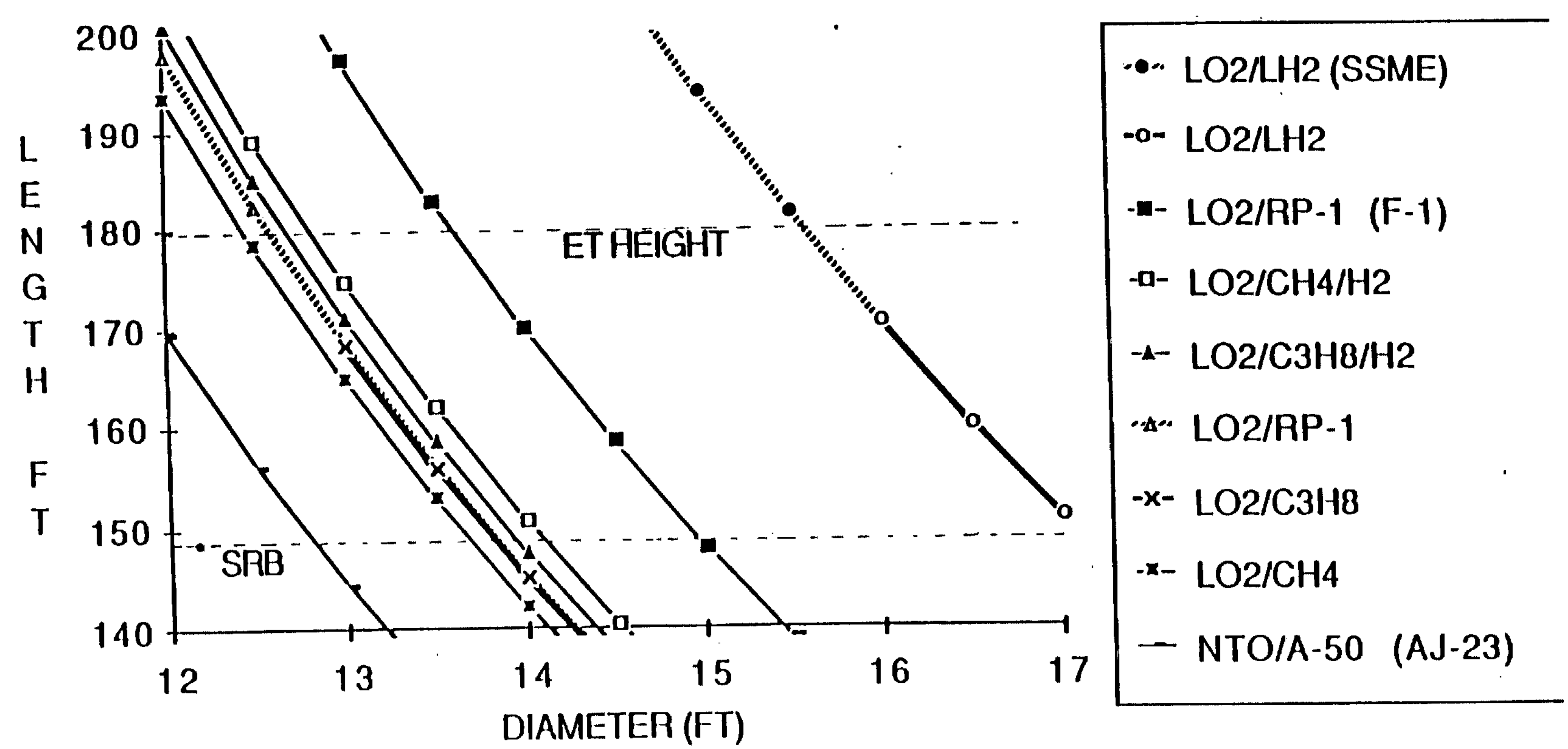
# PROPELLANT EVALUATION

- **PROPELLANT TYPES ANALYZED**
  - LO2/HC
  - LO2/HC/LH2
  - LO2/LH2
  - NTO/MMH

- **EVALUATION CRITERIA**
  - SAFETY
  - STS COMPATIBILITY (SIZE)
  - PERFORMANCE
  - COST
  - SCHEDULE RISK
  - TECHNICAL RISK
  - OPERATIONAL AVAILABILITY
  - OPERATIONAL COMPLEXITY
  - ENVIRONMENTAL IMPACTS
  - GROWTH POTENTIAL

# LENGTH / DIAMETER: PUMP-FED LRB

PC = OPTIMIZED, NOZZLE DIAMETER = 50 IN



# LO2/HC PROPELLANT EVALUATION

## ADVANTAGES

- PERFORMANCE - BETTER Isp DESITY THAN LO2/LH2
- RISK - LOWEST FOR LO2/RP1 (ADEQUATE FLIGHT EXPERIENCE)
- OPERATIONAL AVAILABILITY - EXISTING FACILITIES FOR LO2 & RP1
- OPERATIONAL COMPLEXITY - BETTER THAN HYPERGOLS OR LO2/HC/LH2
- SAFETY - NON-TOXIC; LOWEST EXPLOSIVE HAZARD

## DISADVANTAGES

- COST - ADDITIONAL HC TANKING SYSTEM; NOT AS EXPENSIVE AS LO2/HC/LH2
- ENVIRONMENTAL IMPACTS - CO & CO2 EXHAUST DETRIMENTAL TO OZONE LAYER
- REUSEABILITY - CARBON DEPOSITION PROBLEMS AT HIGH CHAMBER PRESSURE WITH LO2/RP1 & LO2/C3H8 INTRODUCE TECHNOLOGY PROGRAMS
- SAFETY - EXPLOSIVE HAZARD OF C3H8 IS HIGHER THAN CH4 & RP1 DUE TO ITS HEAVY VAPOR

# LO2/HC/LH2 PROPELLANT EVALUATION

## ADVANTAGES

- PERFORMANCE - BETTER Isp DENSITY THAN LO2/LH2
- REUSEABILITY - LIMITS OR ELIMINATES COKING & CARBON DEPOSITION PROBLEMS OF LO2/HC
- ENVIRONMENTAL IMPACTS (PRE-COMBUSTION) - BETTER THAN HYPERGOLS
- OPERATIONAL AVAILABILITY - EXISTING FACILITIES FOR LO2, LH2 & RP1
- LO2/CH4/LH2 IS IN CURRENT STBE STUDIES

## DISADVANTAGES

- COMPLEX CYCLE WITH THREE PROPELLANT TURBOPUMP ARRANGEMENT
- COST - HIGHEST PRODUCTION & DEVELOPMENT COST
- SAFETY - EXPLOSIVE HAZARD IS HIGHER THAN BIPROPELLANTS
- ENVIRONMENTAL IMPACTS - CO & CO2 EXHAUST DETRIMENTAL TO OZONE LAYER
- OPERATIONAL COMPLEXITY - HIGHEST COMPLEXITY IN OPERATIONS & SUPPORT
- RISK - NEW CONCEPT; NO FLIGHT HISTORY
  HIGHEST TECHNOLOGICAL RISK WITH LO2/C3H8/LH2 & LO2/RP1/LH2

# LO2/LH2 PROPELLANT EVALUATION

## ADVANTAGES

- COST - USES EXISTING SYSTEMS
- RISK - FLIGHT PROVEN CONCEPT; LOWEST DEVELOPMENT RISK
- REUSEABILITY - BEST CLEAN BURNING
- ENVIRONMENTAL IMPACTS - MINIMAL
- OPERATIONAL AVAILABILITY - COMPATIBLE WITH EXISTING SYSTEM
- OPERATIONAL COMPLEXITY - BETTER THAN HYPERGOLS AND LO2/HC/LH2
- SAFETY - NON TOXIC

## DISADVANTAGES

- BOOSTER SIZE - LARGEST OF ALL PROPELLANTS
- SAFETY - HIGHLY EXPLOSIVE

# NTO/HYDRAZINES PROPELLANT EVALUATION

## ADVANTAGES

- STS COMPATIBILITY - SMALL BOOSTER SIZE
- REUSEABILITY - CLEAN BURNING
- RELIABILITY - EXCELLENT COMBUSTION CHARACTERISTICS, EASY TO SEAL
- ENVIRONMENTAL IMPACT (POST-COMBUSTION) - RELATIVELY INERT EXHAUST PRODUCTS
- STORABLES - NO INSULATION SYSTEMS REQUIRED, SOME FLEXIBILITY IN LOADING TIME

## DISADVANTAGES

- SAFETY - HIGH TOXICITY, MMH/A-50 SUSPECTED CARCINOGENS; HIGH EXPLOSIVE HAZARDS (2-5% IN AIR)
  EXPOSURE LIMIT: 3 ppm FOR NTO; 0.2 ppm FOR MMH; 0.5ppm FOR UDMH
- ENVIRONMENTAL IMPACTS - SPILLS CLEANUP POSES HAZARDOUS WASTE ISSUE
  IN CASE OF EXPLOSION (ABORT OR ACCIDENT SCENARIOS), ATMOSPHERIC DISPERSION OF TOXIC PLUME
  NTO - FORMS ACID WITH WATER, PHOTOCHEMICAL SMOG
  HYDRAZINES - SOLUBLE IN WATER, FORM TOXIC BY-PRODUCTS
- PROPELLANT AVAILABILITY - ONLY ONE EXISTING MANUFACTURER FOR EACH PROPELLANT.
  FOR LRB QUANTITIES REQUIRED, NEW PLANTS MAY BE NEEDED. ~3-5 YRS TO QUALIFY NEW VENDOR
- COST - MOST EXPENSIVE LIQUID PROPELLANT (2.75$/LB NTO & 10$/LB MMH, ~12M$/LAUNCH)
  HIGH FACILITY ACTIVATION COST
- OPERATIONAL COMPLEXITY - COMPLEX LAUNCH PROCESSING PROCEDURES DUE TO SAFETY CONCERNS
- LAUNCH SCHEDULE IMPACT - DOWNWIND HAZARD CONCERNS
- RECOVERY/REFURBISHMENT - COMPLEX PROCEDURES DUE TO TOXICITY OF RESIDUES

# PROPELLANT EVALUATION
## Comparison Matrix

| QUALITATIVE EVALUATION<br>RANKING GRADE<br>A - BEST<br>B<br>C<br>D<br>F - WORST | NEW/EXPENDABLE | | | | | NEW/REUSABLE | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | LO2/LH2 | LO2/CH4 | LO2/C3H8 | LO2/RP-1 | NTO/MMH | LO2/LH2 | LO2/CH4 | LO2/CH4/LH2 | LO2/C3H8/LH2 | LO2/RP-1/LH2 | NTO/MMH |
| SAFETY | C | B | B | A | F | C | B | C | C | C | F |
| RELIABILITY | B | C | D | D | A | B | C | C | D | D | A |
| STS COMPATIBILITY (SIZE) | F | B | B | B | A | F | C | D | B | B | A |
| PERFORMANCE | YES | YES | YES | YES | YES | YES | YES | YES | YES | YES | YES |
| COST (?) NON-RECURRING | B | C | C | B | C | C | D | D | F | F | D |
| RECURRING | C | C | C | C | D | B | B | C | C | C | C |
| SCHEDULE RISK | B | C | C | B | D | B | C | D | F | F | D |
| TECHNICAL RISK | B | C | C | B | B | C | D | D | F | F | C |
| OPERATIONAL AVAILABILITY | | | | | | A | B | C | C | C | C |
| OPERATIONAL COMPLEXITY | C | B | C | A | F | C | D | F | F | F | F |
| ENVIRONMENTAL IMPACTS | A | B | C | C | F | A | B | C | C | C | F |
| GROWTH POTENTIAL (?) | A | B | B | B | C | A | B | B | B | B | C |

# PUMP-FED PROPELLANT EVALUATION SUMMARY

- ALTHOUGH NTO/HYDRAZINES, INCLUDING AJ23, CANDIDATES HAVE LOWEST PROPELLANT VOLUME THEIR SAFETY & ENVIRONMENTAL IMPACT DISADVANTAGES ARE SEVERE.

- FOR THE EXISTING ENGINES, SSME-35 (LO2/LH2) IS PREFERABLE IF ITS LARGE SIZE DISADVANTAGE DOES NOT PROHIBIT INTEGRATION TO THE STS. THE LARGE THRUST SIZE OF THE F-1 RESTRICTS ENGINE OUT CAPABILITY

- FOR REUSABLE CONCEPT, PERFORMANCE ADVANTAGES OF LO2/HC/LH2 DO NOT APPEAR TO OFFSET DISADVANTAGES OF INCREASED COMPLEXITY AND COST OVER BIPROPELLANTS. LO2/RP1 IS ALSO BEING RECONSIDERED FOR REUSABLE CONCEPT BECAUSE OF ITS LOW TANK VOLUME.

- FOR EXPENDABLE CONCEPT, LO2/HC OPTIONS HAVE VERY SIMILAR PROPELLANT VOLUME, SAFETY AND ENVIRONMENTAL IMPACT. MORE DETAILED EXAMINATION OF THESE OPTIONS ARE BEING DONE.

UPDATE ON T.S. 1.5 PUMP-FED PROPELLANT SELECTION

The data in this trade study was a major element in concept selection. After the midterm review, we stopped considering reusability, but cost and risk considerations became more important.

On 5/16/88 our selected concepts all use LOX/HC propellants:

LOX/RP-1 AND LOX/CH4

Higher cost estimates eliminated SSME before the midterm and new LOX/LH2 pump-fed engines just recently. Reduced costs, perhaps by sharing with the ALS program, would make LOX/LH2 a very viable candidate for LRB.

LIQUID ROCKET BOOSTER
TRADE STUDY ERB
DECEMBER 4, 1987

TRADE STUDY 1.6
FINAL ERB

# PRESSURE FED - PROPELLANT SELECTION

STUDY LEADER: TINA NGUYEN

SYSTEMS ENGINEER: MIKE VACCARO

**GENERAL DYNAMICS**
*Space Systems Division*

# 1.6 PRESSURE FED - PROPELLANT SELECTION Planning Sheet 2

## REQUIREMENTS:

1. 70 KLB PAYLOAD TO 150 NM ORBIT, 28.5 DEG INCLINATION, WITH ORBITER SSME'S LIMITED TO 100% PL
2. 59 KLB PAYLOAD TO 150 NM ORBIT, 28.5 DEG INCLINATION, WITH ORBITER SSME'S LIMITED TO 104% PL
3. SATISFY STS TRAJECTORY CONSTRAINTS (MAX Q, LIFTOFF T/W, MAX G, ETC.)

## CONSTRAINTS:

- IMPROVE SAFETY, RELIABILITY AND ENVIRONMENTAL ACCEPTABILITY
- MINIMIZE IMPACT/CHANGES ON ET, ORBITER, LAUNCH SITE AND GSE
- MINIMIZE IMPACTS TO FLAMETRENCH - MAXIMUM De IS LIMITED TO 90in

# 1.6 PRESSURE FED - PROPELLANT SELECTION Planning Sheet 1

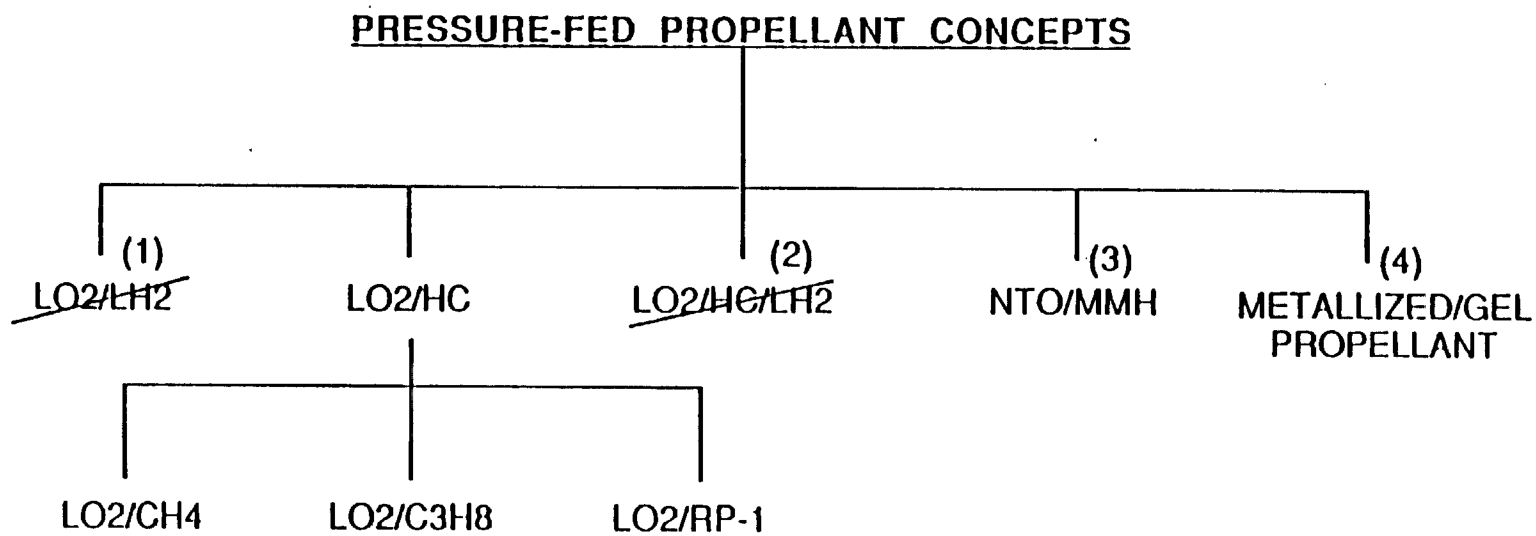
## OBJECTIVE:

SELECT THE BEST PROPELLANT COMBINATION(S) FOR A PRESSURE FED LIQUID ROCKET BOOSTER

## GROUNDRULES/ASSUMPTIONS

- CONFIGURATION = CONVENTIONAL CYLINDRICAL (CURRENT SRB)
- VEHICLE L/D RATIO = 12.3
- NUMBER OF ENGINES = 4
- TANK MATERIAL = GRAPHITE-EPOXY
- PRESSURIZATION SYSTEM = GAS GENERATOR HEATED HELIUM SYSTEM
- EXIT DIAMETER = 90 IN (NO MODIFICATION TO FLAME TRENCH)
- CHAMBER PRESSURE = 400 PSIA
- MIXTURE RATIO = FIXED (ISP OPTIMIZED)
  - SENSITIVITY RUNS SHOWED ONLY HIGHER ORDER EFFECT ON PROPELLANT VOLUME

# 1.6 PRESSURE FED - PROPELLANT SELECTION
## Planning Sheet 4
## Trade Tree




(1) NOT CONSIDERED BECAUSE OF LARGE BOOSTER SIZE
(2) NO ADVANTAGES FOR PRESSURE-FED APPLICATION
(3) MAY BE ELIMINATED EARLY IN TRADE DUE TO SAFETY & ENVIRONMENTAL IMPACT CONCERNS
(4) CONSIDERED AS CANDIDATE FOR FUTURE APPLICATION ONLY DUE TO TECHNOLOGY RISK

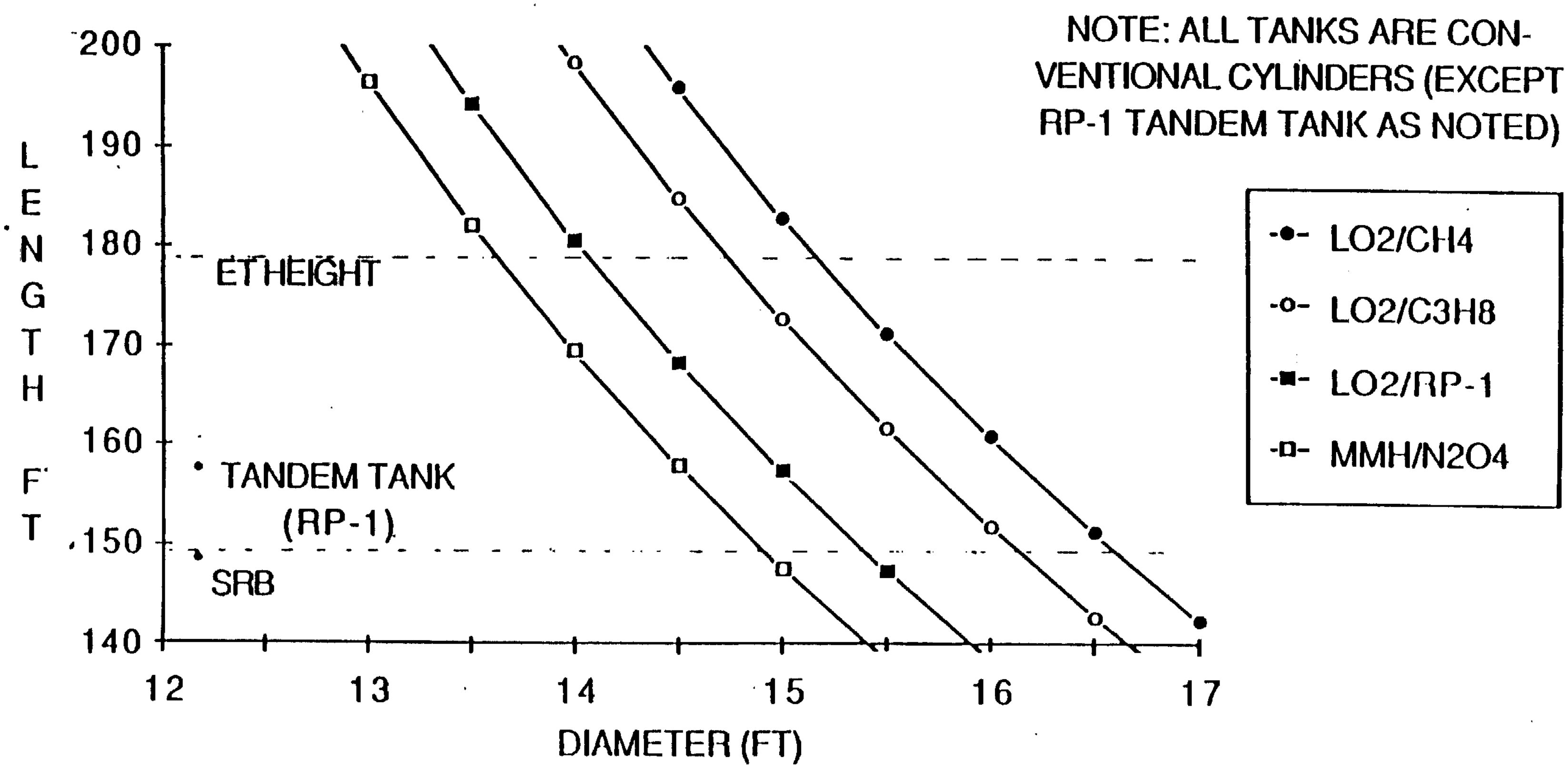
# PROPELLANT EVALUATION

- **PROPELLANT OPTIONS ANALYZED**
  - LO2/CH4
  - LO2/C3H8
  - LO2/RP1
  - NTO/MMH

- **EVALUATION CRITERIA**
  - SAFETY
  - STS COMPATIBILITY (SIZE)
  - PERFORMANCE
  - COST
  - SCHEDULE RISK
  - TECHNICAL RISK
  - OPERATIONAL AVAILABILITY
  - OPERATIONAL COMPLEXITY
  - ENVIRONMENTAL IMPACTS
  - GROWTH POTENTIAL

# LENGTH / DIAMETER: PRESSURE-FED LRB

PC = 400 PSI, NOZZLE EXIT DIAMETER = 90 IN



# NTO/MMH PROPELLANT EVALUATION

## ADVANTAGES

- STS COMPATIBILITY - SMALLEST BOOSTER
- REUSEABILITY - CLEAN BURNING
- RELIABILITY - EXCELLENT COMBUSTION CHARACTERISTICS
- ENVIRONMENTAL IMPACT (POST-COMBUSTION) - RELATIVELY INERT EXHAUST PRODUCTS
- STORABLES - NO VENT OR INSULATION SYSTEMS REQUIRED

## DISADVANTAGES

- SAFETY - HIGH TOXICITY, MMH IS SUSPECTED CARCINOGEN; HIGH EXPLOSIVE HAZARDS (~4.7% IN AIR)
  EXPOSURE LIMIT: 3 ppm FOR NTO; 0.2 ppm FOR MMH
- ENVIRONMENTAL IMPACTS - SPILLS CLEANUP MAY POSE HAZARDOUS WASTE ISSUE
  IN CASE OF EXPLOSION (ABORT OR ACCIDENT SCENARIOS), ATMOSPHERIC DISPERSION OF TOXIC PLUME
  NTO - FORMS ACID WITH WATER, PHOTOCHEMICAL SMOG
  MMH - SOLUBLE IN WATER, FORM TOXIC BY-PRODUCTS
- PROPELLANT AVAILABILITY - ONL;Y ONE EXISTING MANUFACTURER FOR EACH PROPELLANT.
  FOR LRB QUANTITIES REQUIRED, NEW PLANTS MAY BE NEEDED. ~3-5 YRS TO QUALIFY NEW VENDOR
- COST - MOST EXPENSIVE PROPELLANT (2.75\$/LB NTO & 10\$/LB MMH, ~12M\$/LAUNCH)
  HIGH FACILITY ACTIVATION COST
- OPERATIONAL COMPLEXITY - COMPLEX LAUNCH PROCESSING PROCEDURES DUE TO SAFETY CONCERNS

# METALLIZED/GEL PROPELLANT EVALUATION

## ADVANTAGES

- SAFETY - EXPLOSIVE HAZARD IS LESS THAN LIQUIDS IN HANDLING & STORAGE
- HIGHEST Isp DENSITY COMPARED TO ALL CONVENTIONAL LIQUIDS
- STORABLE - FLEXIBILITY IN LOADING TIME

## DISADVANTAGES

- TRANSFER - HIGH VISCOSITY AS GEL, RHEOLOGY IS NOT WELL UNDERSTOOD, EVACUATED TANKS MAY BE REQUIRED TO AVOID BUBBLE ENTRAPMENT
- UNLOADING OF PROPELLANT IN CASE OF ABORT MAY NOT BE POSSIBLE
- CORING IN TANK - POSITIVE EXPULSION DEVICE (EG. PISTON) MAY BE REQUIRED
- AVAILABILITY - ONLY PRODUCED IN SMALL QUANTITIES SO FAR. FOR LARGE QUANTITIES, NEW PRODUCTION PLANTS MAY BE REQUIRED
- COST - PROPELLANT COST WOULD PROBABLY BE HIGHEST. TRANSFER WILL BE EXPENSIVE.
- ENVIRONMENTAL IMPACTS - SOLID PARTICULATES ($Al_2O_3$) IN EXHAUST PRODUCTS
- TECHNICAL AND SCHEDULE RISK - NEW DEVELOPMENT WHERE MANY PROBLEMS ARE IDENTIFIED AND NOT YET RESOLVED
- OPERATIONAL COMLEXITY - NEW FACILITY, TRANSFER, ETC
- OPTIONS INCLUDE AL/HYPERGOLS & AL/LO2/RP1

# PRESSURE FED - PROPELLANT EVALUATION
## Comparison Matrix

| RANKING GRADE<br>A - BEST<br>B<br>C<br>D<br>F - WORST | QUALITATIVE EVALUATION | | | |
|---|---|---|---|---|
| | LO2/CH4 | LO2/C3H8 | LO2/RP1 | NTO/MMH |
| SAFETY | B | B | A | F |
| RELIABILITY | B | B | B | A |
| STS COMPATIBILITY | D | C | B | A |
| PERFORMANCE | YES | YES | YES | YES |
| COST | B | B | B | C |
| SCHEDULE RISK | B | B | B | C |
| TECHNICAL RISK | B | B | A | A |
| OPERATIONAL AVAILABILITY | B | B | B | F |
| OPERATIONAL COMPLEXITY | B | B | A | C |
| ENVIRONMENTAL IMPACTS | B | B | B | F |
| GROWTH POTENTIAL | B | B | B | C |

7A

# PRESSURE FED - PROPELLANT SELECTION
## Summary of Results

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**CONCLUSIONS:**

- LO2/RP1 APPEARS TO BE THE BEST LO2/HC PROPELLANT BASED ON STS COMPATIBILITY (SIZE)
- NTO/MMH SHOWS THE BEST STS SOMPATIBILITY (SIZE), BUT ITS OPERATIONS, SAFETY & ENVIRONMENTAL IMPACTS DISADVANTAGES MAY ELIMINATE THIS CONCEPT
- METALLIZED PROPELLANT WILL BE CONSIDERED FOR FUTURE RATHER THAN IMMEDIATE APPLICATION DUE TO PRESENT TECHNOLOGY RISKS

LIQUID ROCKET BOOSTER
TRADE STUDY ERB
JANUARY 12, 1988

TRADE STUDY 1.7
FINAL ERB

# PRESSURE FED

# CHAMBER PRESSURE SELECTION

STUDY LEADER: BILL PIERCE

SYSTEMS ENGINEER: MIKE VACCARO

**GENERAL DYNAMICS**
*Space Systems Division*

# 1.7 PRESSURE FED - CHAMBER PRESSURE SELECTION
## Planning Sheet 2

**REQUIREMENTS:**

1. 70 KLB PAYLOAD TO 150 NM ORBIT, 28.5 DEG INCLINATION, WITH ORBITER SSME'S LIMITED TO 100% PL
2. 59 KLB PAYLOAD TO 150 NM ORBIT, 28.5 DEG INCLINATION, WITH ORBITER SSME'S LIMITED TO 104% PL

**CONSTRAINTS:**

- AERODYNAMIC LOAD ON ORBITER WING AT MAX Q
  - NEED TO MINIMIZE PROPELLANT TANK VOLUME
- FLAME TRENCH WIDTH
  - NEED TO MINIMZE ENGINE NOZZLE

# 1.7 PRESSURE FED CHAMBER PRESSURE SELECTION
## Planning Sheet 4
## Trade Tree

SEPARATE TRADES FOR THE FOLLOWING PROPELLANT COMBINATIONS

~~NTO/MMH~~ LO2/RP1 LO2/CH4 ~~LO2/C3H8~~

De = 90

*Pc = 250 Pc = 400 Pc = 700 Pc = 1000

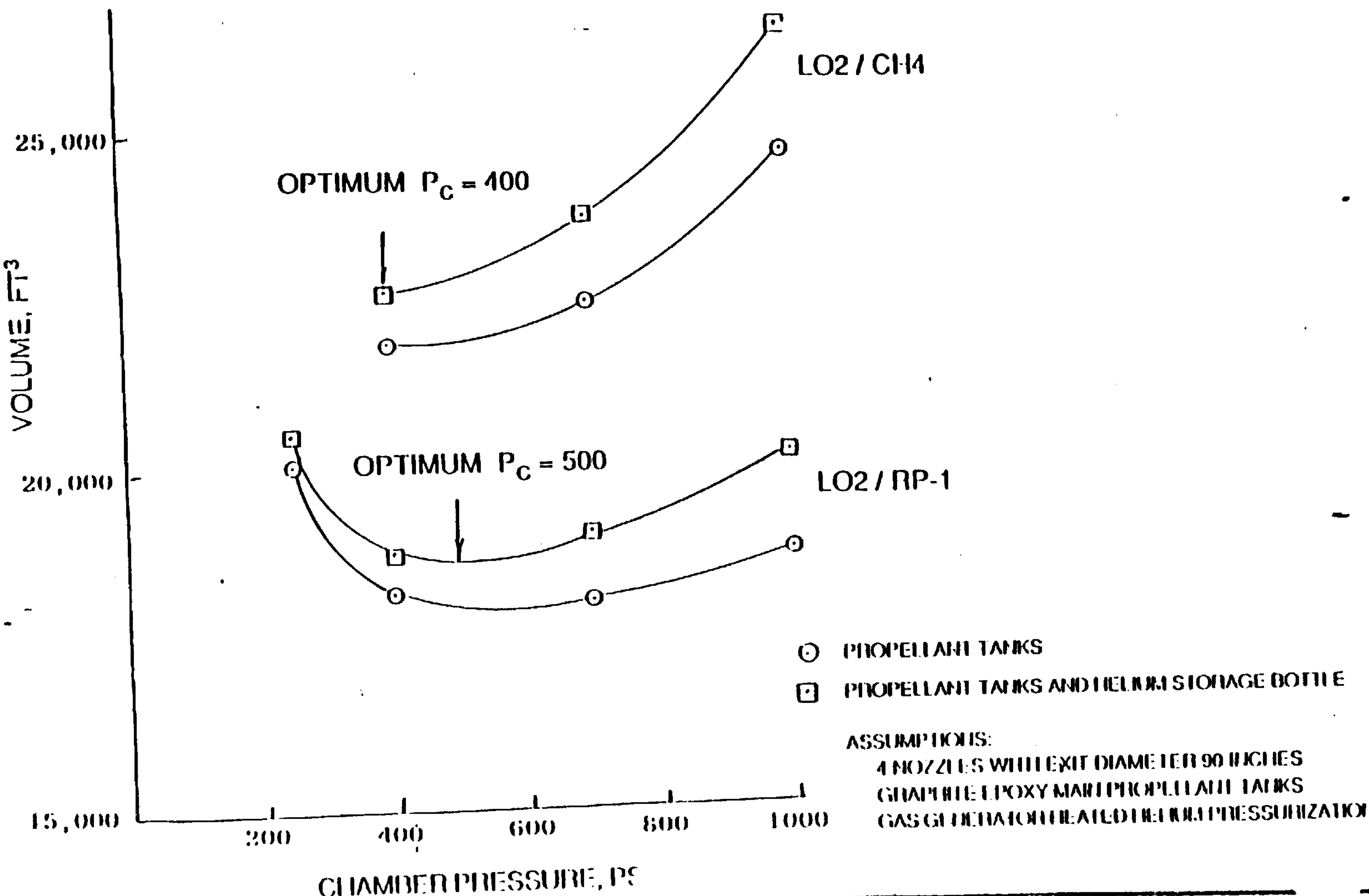
NOTE: NTO/MMH ELIMINATED BY DOWNSELECTION BEFORE CHAMBER PRESSURE SELECTION DATA WAS OBTAINED AND LO2/C3H8 PERFORMANCE WAS ASSUMED TO BE BETWEEN RP1 AND CH4 PERFORMANCE.

* FOR LO2 /RP1 ONLY

GENERAL DYNAMICS
Space Systems Division

# CHAMBER PRESSURE OPTIMIZATION FOR MINIMUM VEHICLE VOLUME

LRB



# T.S. 1.7 PRESSURE FED CHAMBER PRESSURE SELECTION

## Summary of Results

### CONCLUSIONS:

- THERE IS NO SIGNIFICANT CHANGE IN TANK VOLUME FOR CHAMBER PRESSURE OF 400 TO 700 PSIA

- THE NOMINAL CHAMBER PRESSURE SHOULD BE 400 PSIA, AS LOWER PRESSURE IS BETTER FROM THE SAFETY STANDPOINT.

### RECOMMENDATIONS:

- THIS OPTIMUM CHAMBER PRESSURE STUDY SHOULD BE REPEATED FOR L02/RP-1 WHEN THE CONFIGURATION, TRAJECTORY AND THRUST PROFILE ARE BETTER DEFINED.

## UPDATE ON T.S. 1.7 OPTIMUM CHAMBER PRESSURE

This trade was performed assuming advanced technology graphite-epoxy propellant tanks (see Trade 1.12). The answer is also strongly dependent on pressurization system weights (see Trade 1.14). Pressure fed engine features such as gimbaling and cooling also had to be assumed before Propulsion Subcontractor trades were complete. Based on these assumptions, we recommended a Chamber Pressure of 400 psi.

Subsequently there have been major changes. As of 5/13/88, we feel the optimum Chamber Pressure is approximately 330 psi. This is based on 2219 aluminum tanks, because of the high risk associated with graphite epoxy liquid propellant tanks (particularly for LOX). Work is continuing to consider nozzle exit diameter limits due to the KSC facilities, gimbaling high pressure inlet lines, feed line arrangements, and the risk of combustion instability throttling at this chamber pressure.

LIQUID ROCKET BOOSTER
TRADE STUDY ERB
FEBRUARY 3, 1988

TRADE STUDY 1.12
FINAL REPORT

# TANK CONFIGURATION SELECTION

STUDY LEADER: TODD SACZALSKI

SYSTEMS ENGINEER: GREG FARMER/L. PENA

**GENERAL DYNAMICS**
*Space Systems Division*

# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION
## Planning Sheet 1

### OBJECTIVE:

DEVELOP A TYPICAL TANK DESIGN FOR BOTH PUMP AND PRESSURE FED SYSTEMS AND PROVIDE A RECOMMENDED CONFIGURATION FOR EACH TYPE OF PROPELLANT SYSTEM. THE DESIGN WILL INCLUDE STRUCTURE, INSULATION AND THERMAL PROTECTION SYSTEM DEFINITION.

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### GROUNDRULES/ASSUMPTIONS/GUIDELINES:

BOOSTER L/D = 12.3
FULLY REUSEABLE LRB
TANK FACTOR OF SAFETY 1.4
GRAPHITE/EPOXY STRESS ALLOWABLES = 100 (ksi)

# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION
## Planning Sheet 2

REQUIREMENTS:

PRELAUNCH SUPPORT - THE LRBs MUST SUPPORT THE ENTIRE STS VEHICLE ON THE MLP DURING GROUND OPERATIONS

LAUNCH LOADS - THE LRBs SHALL BE CAPABLE OF WITHSTANDING INDUCED LOADS DURING THE LAUNCH PERIOD.

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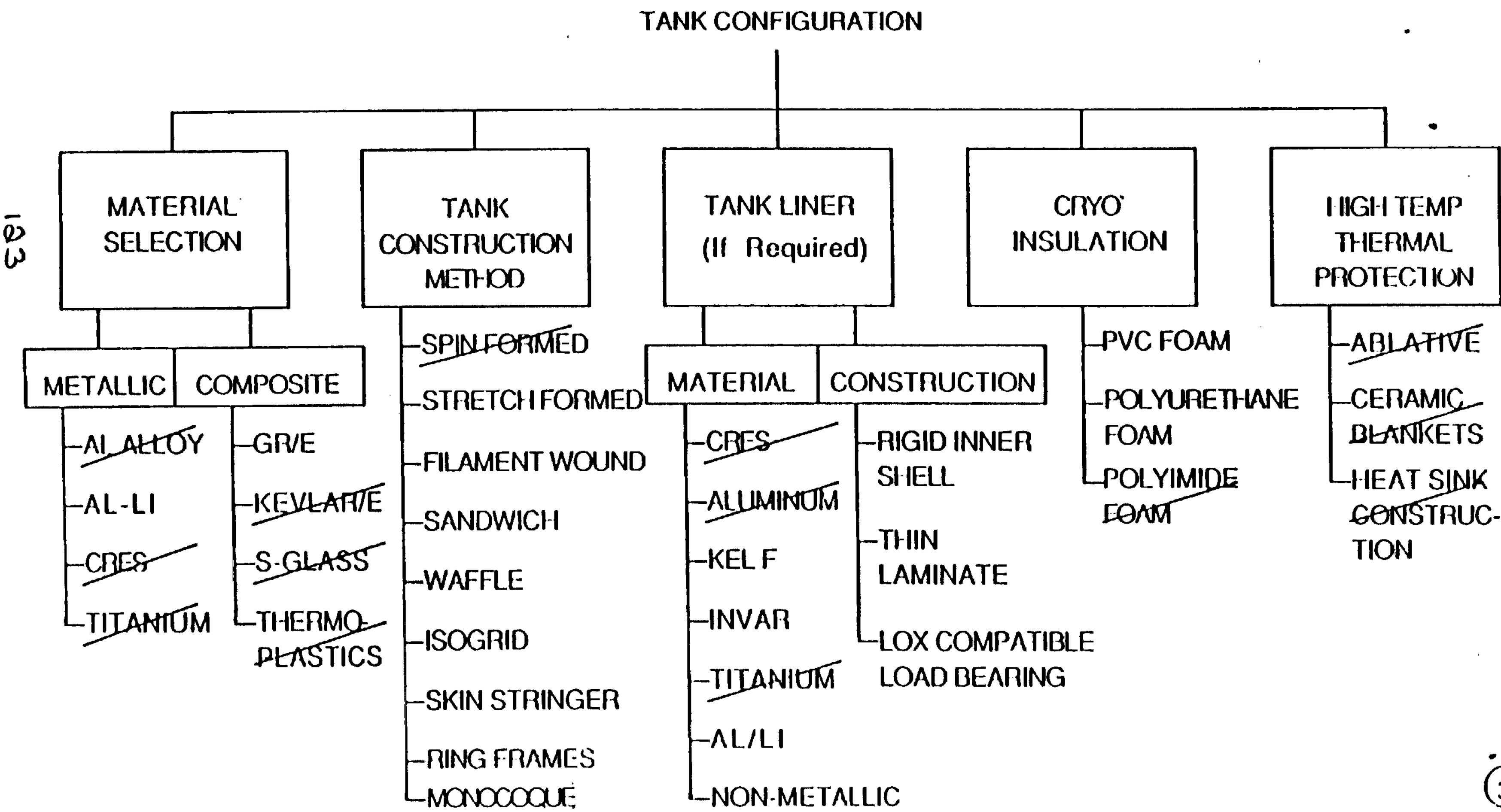
CONSTRAINTS:

INDIVIDUAL TANK L/D RATIO
MATERIAL PROPERTIES
MATERIAL COMPATABILITY
MATERIAL STRESS ALLOWABLES
MAXIMUM TANK DIAMETER = 15 FT.
MAXIMUM VEHICLE LENGTH = 200 FT.

# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION
## Planning Sheet 4

## Trade Tree

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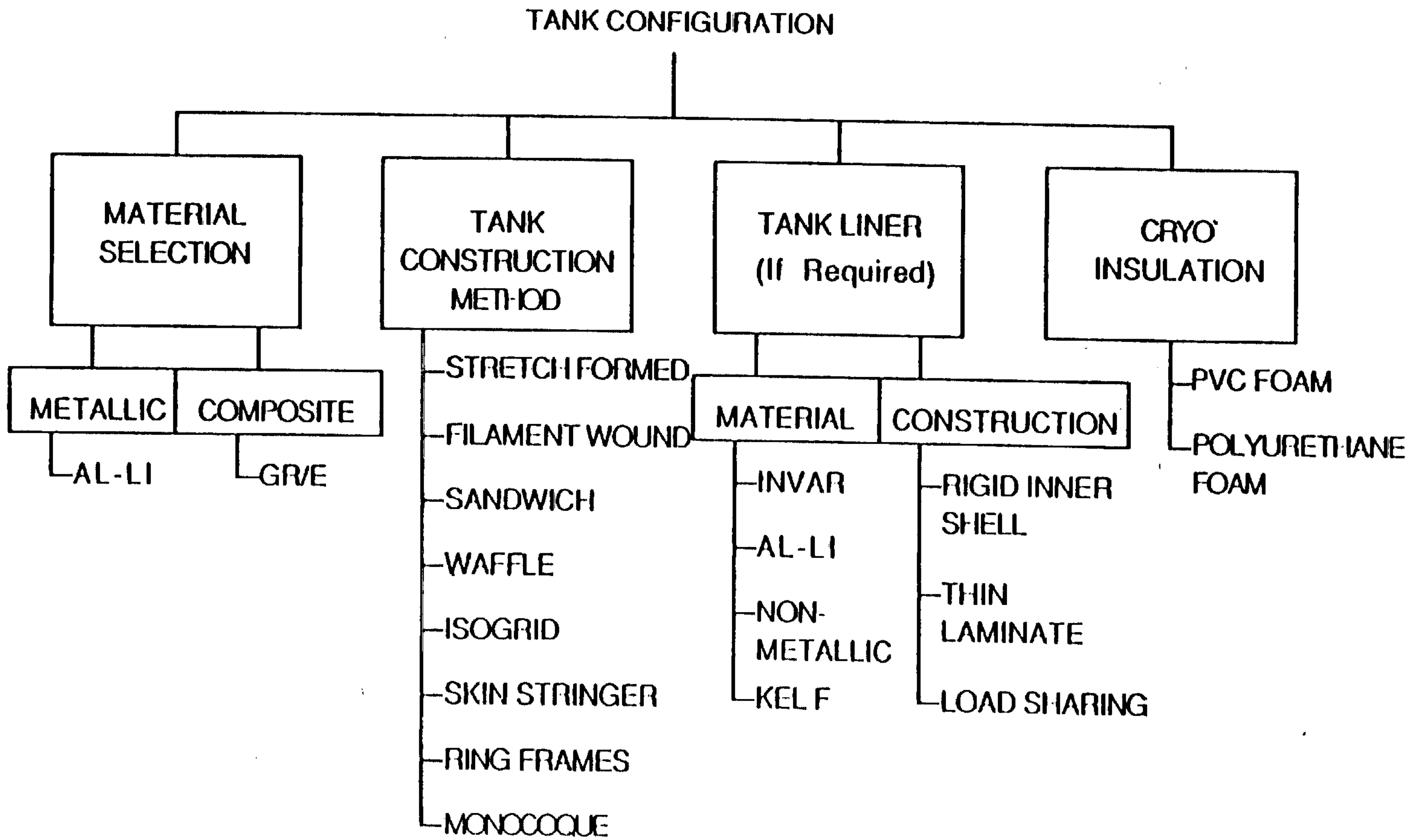
# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION
## Planning Sheet 4

## Trade Tree



# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION
## Planning Sheet 5

**INPUTS:**

THE FOLLOWING INFORMATION WILL NEED TO BE PROVIDED:
- PROPELLANT QUANTITY
- NUMBER, TYPE AND SIZE OF ENGINES
- THERMAL HEATING PROFILE
- AERO AND STRUCTURAL LOADS PROFILE
- TANK OPERATING PRESSURE

**OUTPUTS:**

DESIGN TANK DRAWINGS FOR EACH TYPE OF PROPELLANT SYSTEM

INTERFACE REQUIREMENTS

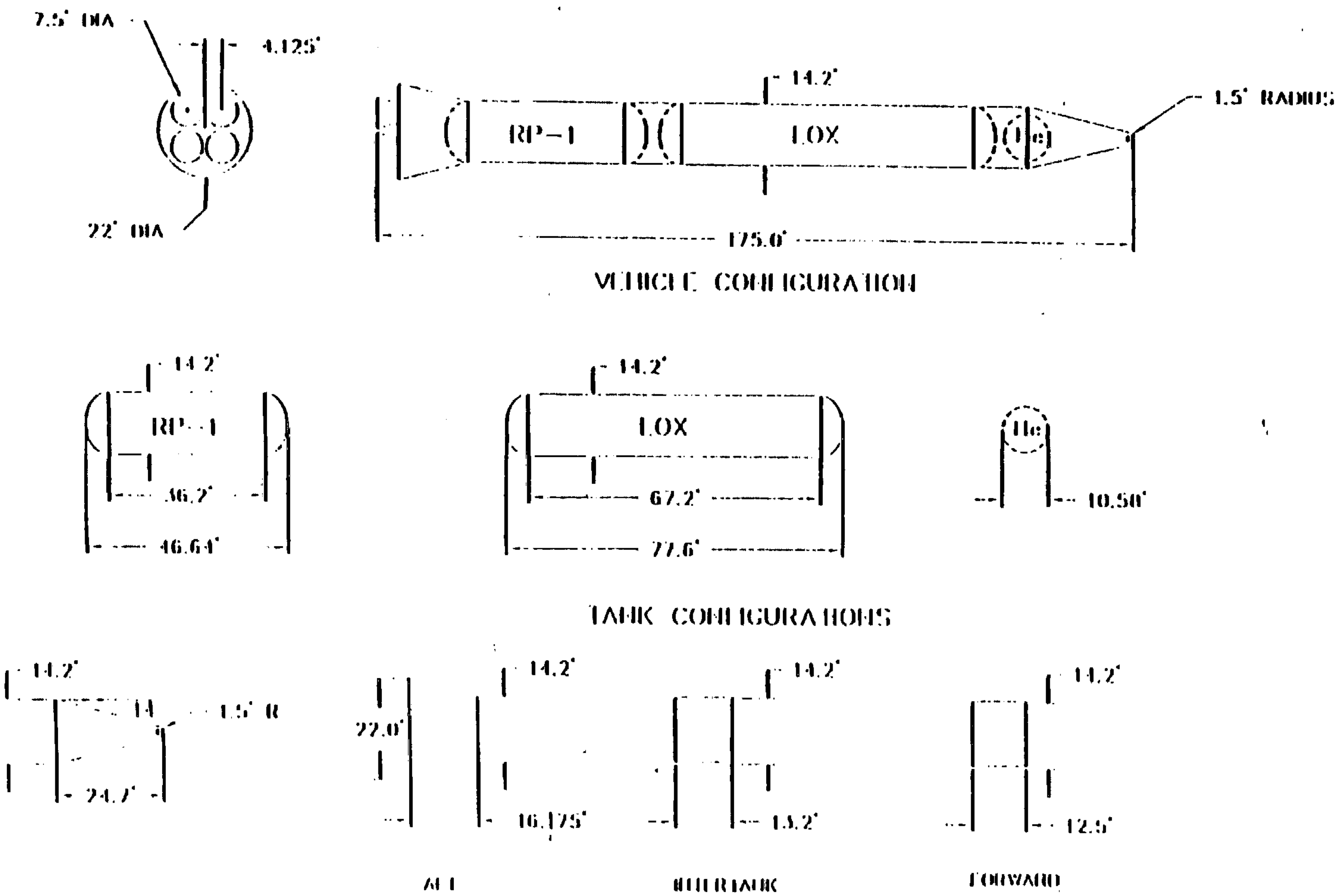
DEVELOP BACK-UP MATERIAL

**OTHER TRADES AFFECTED:**

1.13 RECOVERY SYSTEMS SELECTION
1.14 PRESSURIZATION SYSTEM SELECTION
2.4 DEGREE OF AUTOMATION
2.5 ROBUSTNESS VS. MAINTAINABILITY
2.6 PRODUCTION SITE OPTIONS

# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION
## Planning Sheet 7

## RP1/LOX PRESSURE FED BOOSTER BASELINE

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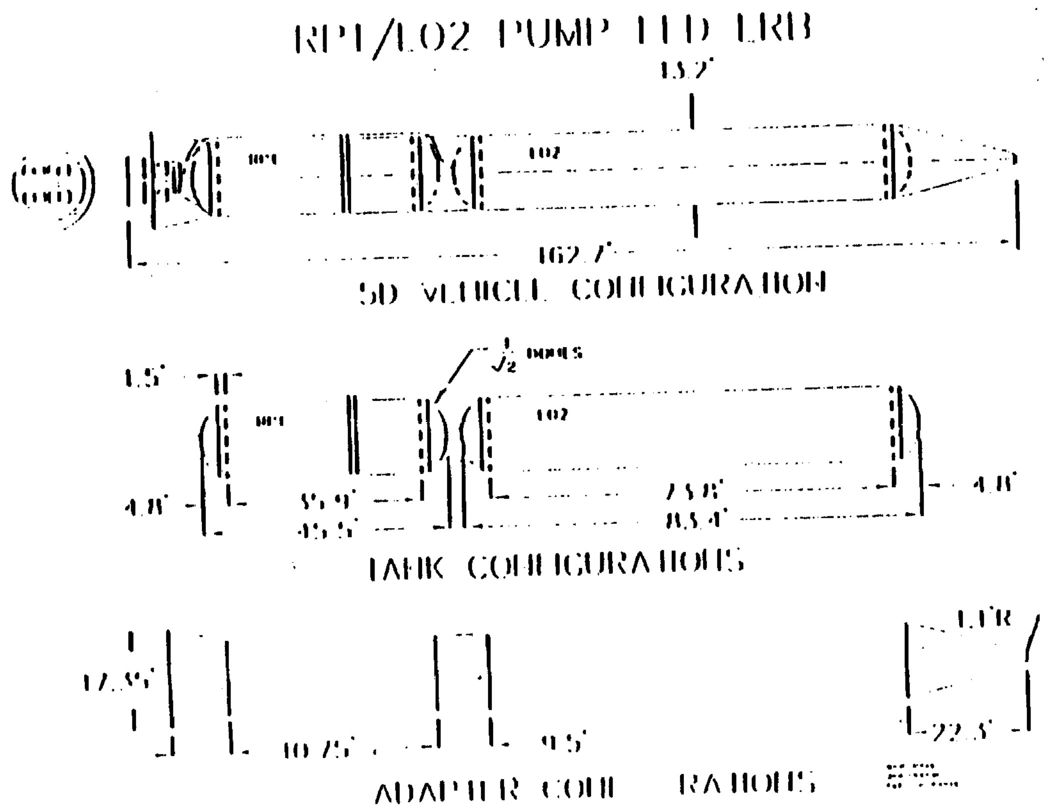
# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION
## Planning Sheet 7

## RP1/LOX PUMP FED BOOSTER BASELINE



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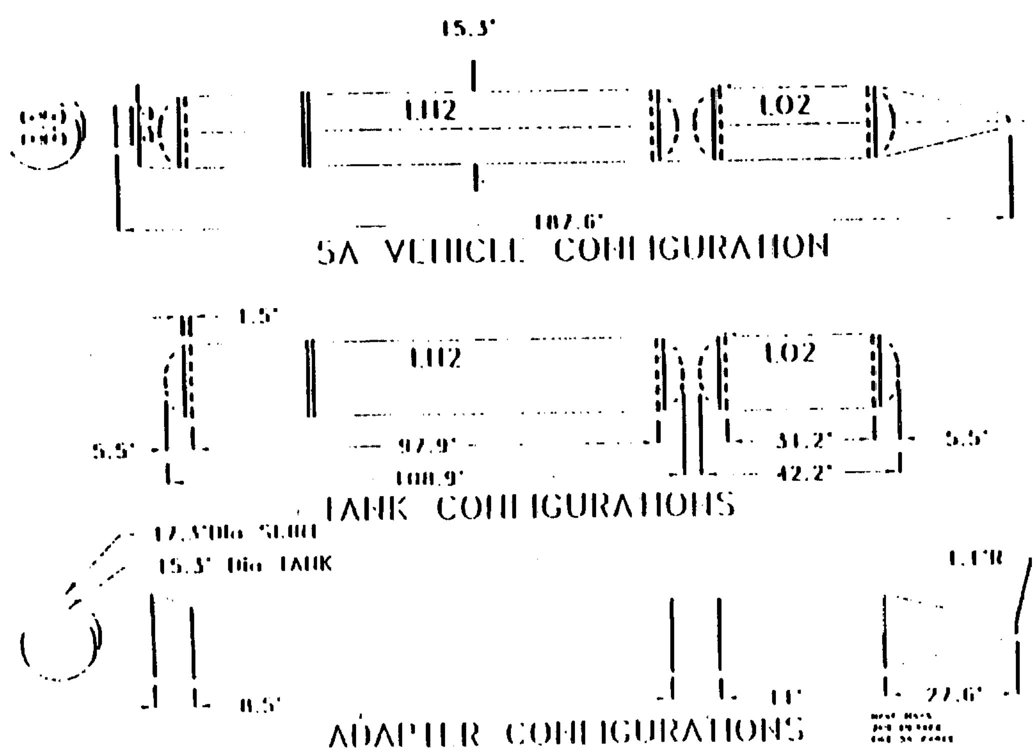
# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION
## Planning Sheet 7

## LH2/LOX PUMP FED BOOSTER BASELINE





GENERAL DYNAMICS
Space Systems Division

# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION
## Planning Sheet 7

## POLAR BOSS DESIGN #1

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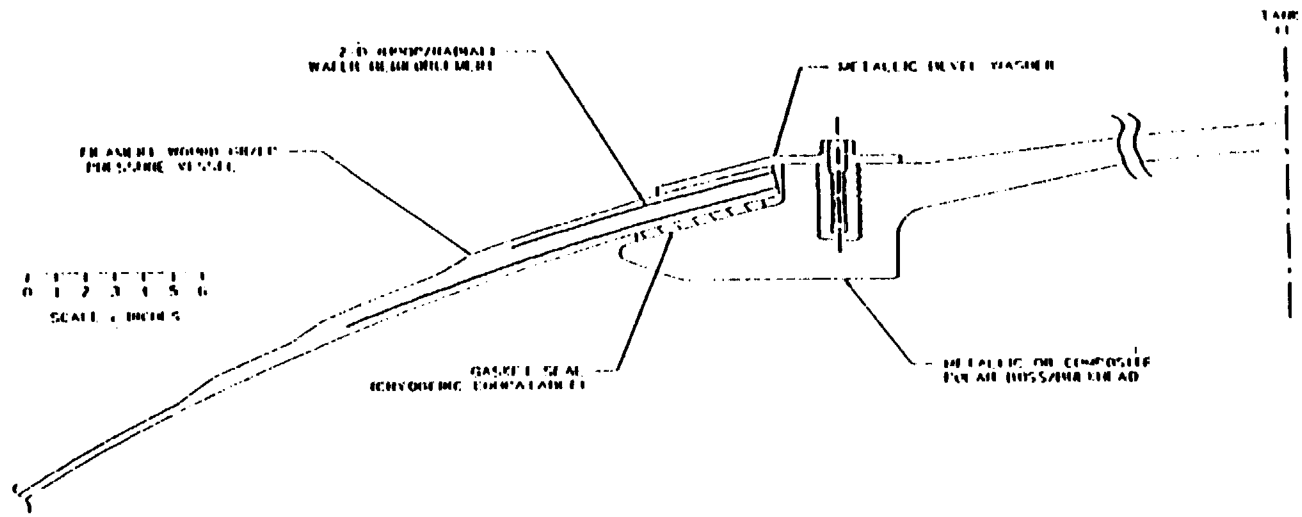


**ADVANTAGES**

- SIMPLE DESIGN
- LOW RISK
- POLAR BOSS [illegible]

**DISADVANTAGES**

- EXCESSIVE MATERIAL
- EXCESSIVE WEIGHT
- CRYO SEALS HARD TO MAKE WORK
- NOT COMPATIBLE WITH LOX
- "CTE" MISMATCH MAY CAUSE SEAL PROBLEMS

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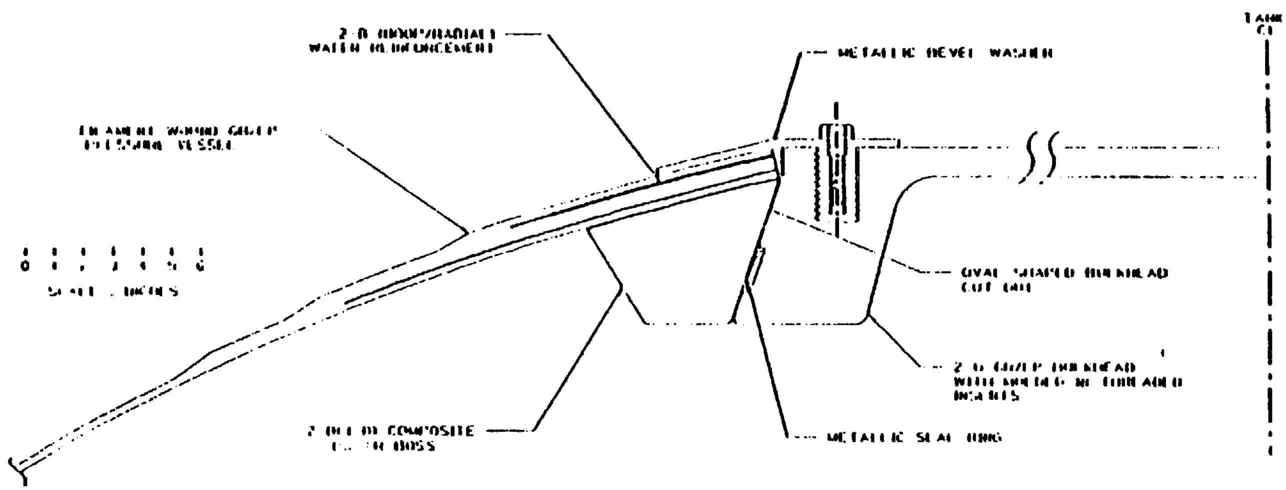
# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION
## Planning Sheet 7

## POLAR BOSS DESIGN #2




ADVANTAGES

- LARGE SEALING SURFACE TO ACCOMMODATE DEFLECTION OF POLAR BOSS & BULKHEAD
- COMPOSITE DESIGN LIGHTER THAN SIMILAR METALLIC DESIGN
- COMPOSITE POLAR BOSS COMBINES STRENGTH/STIFFNESS THAT OUT PERFORMS A METALLIC BOSS DESIGN
- "CTE" RESULTANT DEFLECTIONS ARE LESS OF A PROBLEM

DISADVANTAGES

- LOW LOX COMPATABILITY REQUIRES SPECIAL LINER DESIGN
- METAL INSERTS IN COMPOSITES AT CRYOGENIC TEMPERATURES

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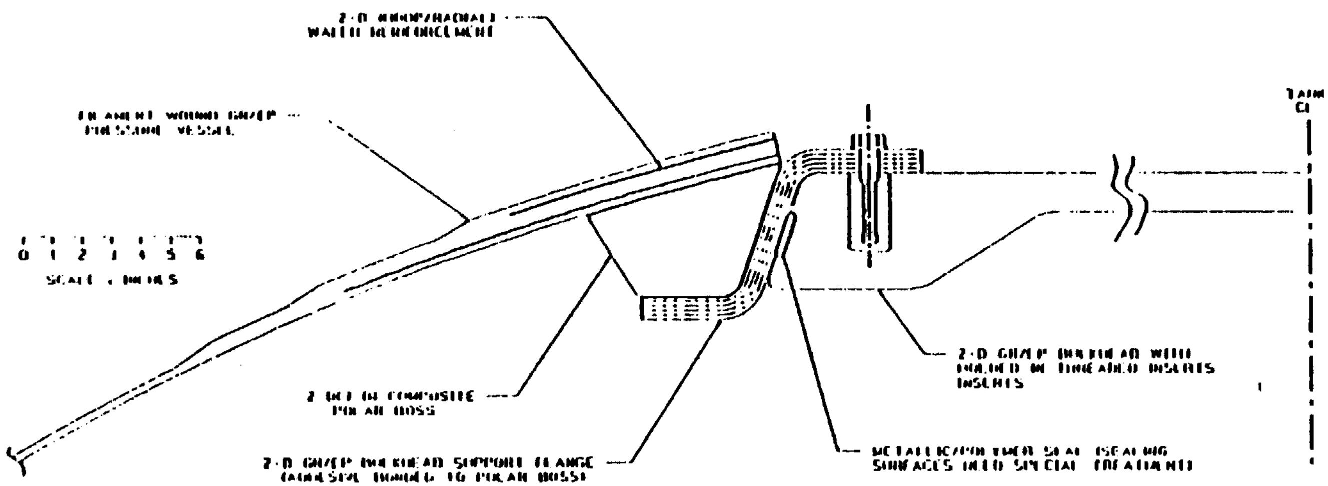
# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION
## Planning Sheet 7

## POLAR BOSS DESIGN #3






### ADVANTAGES

- LIGHT WEIGHT, ALL COMPOSITE DESIGN
- NEGLIGIBLE "CTE" PROBLEMS
- POLAR BOSS/BULKHEAD DESIGN LENDS ITSELF WELL TO THERMOPLASTICS OR "RTM" TECHNIQUES
- EASIER TO SEAL THAN METAL TO COMPOSITE DESIGNS
- SHORT LEAD TIME ON ALL MATERIALS

### DISADVANTAGES

- LINER REQUIRED WITH LOX, MAYBE DIFFICULT TO INCORPORATE WITH THIS DESIGN
- SEALING SURFACES NEED SPECIAL TREATMENT
- BOND LINE BETWEEN PARTS MAY CREATE PROBLEMS AT CRYOGENIC TEMPERATURES

GENERAL DYNAMICS
Space Systems Division

# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION
## Planning Sheet 7

## POLAR BOSS DESIGN #4

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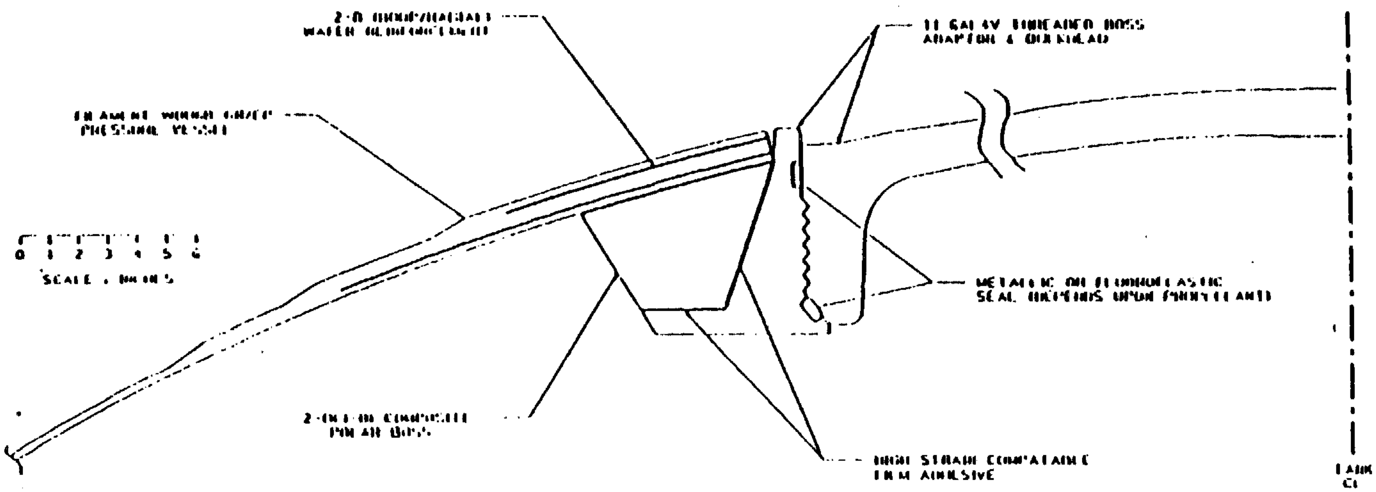


**ADVANTAGES**

- HIGHLY STRESSED AREAS (I.E. THREADS) ARE HANDLED BY A METALLIC DESIGN
- SEALING BETWEEN TWO METAL SURFACES IS BEST
- COMPOSITE POLAR BOSS COMBINES STRENGTH/STIFFNESS THAT OUT-PERFORMS A METALLIC BOSS DESIGN
- COMPOSITE BOSS FABRICATION CAN BE ENGAGED WITH A HIGH LEVEL OF RELIABILITY

**DISADVANTAGES**

- LARGE "CTE" DEFORMATIONS @ CRYOGENIC TEMPERATURES MAY CAUSE DEBOND/DELAMINATION PROBLEMS
- WEIGHT INCREASE WITH USE OF METALLICS
- METAL LINER REQUIRED WITH LOX
- LARGE DIAMETER THREADING DIFFICULT TO PERFORM
- LONG LEAD TIME OF FORGED METAL FITTINGS

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# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION
Planning Sheet 7

## SKIRT AREA DESIGN #1

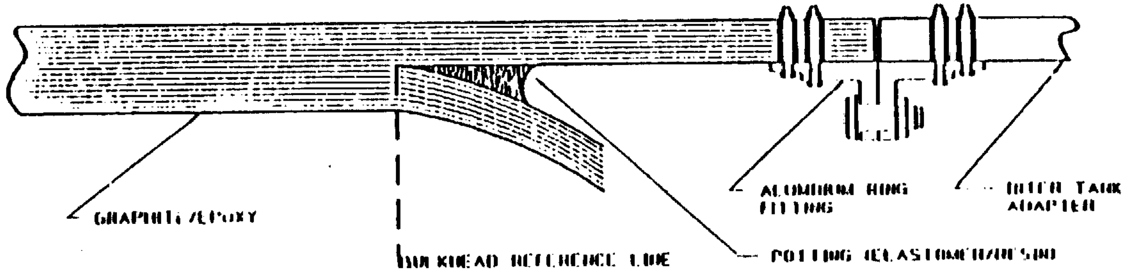


FIGURE 1. COMPOSITE SKIRT AREA WITH ELASTOMER/RESIN INSERTED INTO THE KNUCKLE REGION. NOT TO SCALE.

ADVANTAGES: -[illegible] IN USE
-SKIRT IS AN INTEGRAL PART OF THE TANK FOR HIGH AXIAL LOADS

DISADVANTAGES: EXPENSIVE FABRICATION PROCESS DUE TO EXCESSIVE MATERIAL WASTE

# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION
## Planning Sheet 7

## SKIRT AREA DESIGN #2

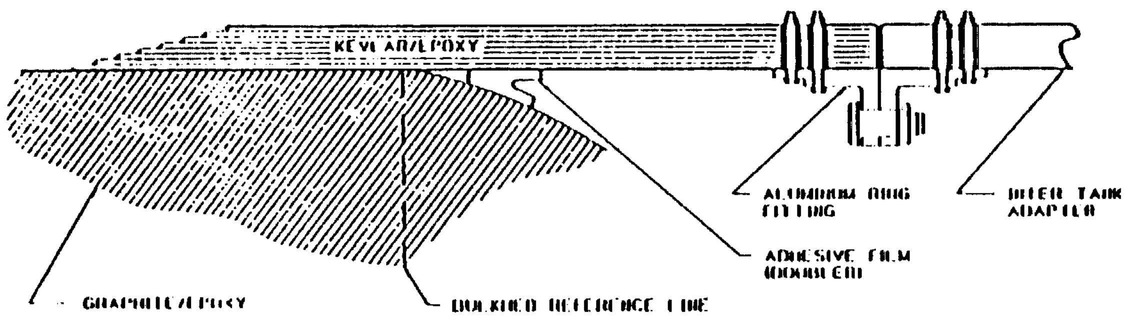


FIGURE 2. COMPOSITE SKIRT AREA WITH AN ADHESIVE FILM DOUBLER INSERTED. NOT TO SCALE.

ADVANTAGES SYSTEM COMMONALITY EXISTS FOR SOLID ROCKET MOTOR CASES
- EASY INSTALLATION OF DOUBLER
- KEVLAR/EPOXY OVERWRAP WILL HELP REDUCE PROBLEMS WITH INTERLAMINAR SHEAR

DISADVANTAGES DOUBLER MUST BE "B STAGE" CURED

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# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION
## Planning Sheet 7

## SKIRT AREA DESIGN #3

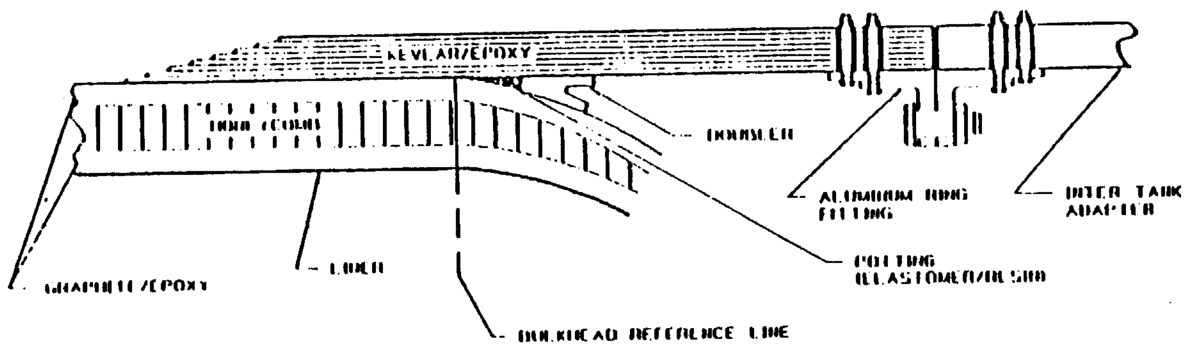


FIGURE 3. COMPOSITE HONEYCOMB SKIRT AREA FOR A PUMP-FED SYSTEM. NOT TO SCALE.

ADVANTAGES
- GOOD COMPRESSIVE STRENGTH RELATIVE TO A THIN LAMINATE STRUCTURE
- LIGHTWEIGHT STRUCTURE RELATIVE TO A METALLIC STRUCTURE
- KEVLAR/EPOXY OVERWRAP WILL HELP REDUCE PROBLEMS WITH INTERLAMINAR SHEAR DUE TO ITS DUCTILITY.

DISADVANTAGES
- EXTREMELY HARD TO FABRICATE
- HIGH COST
- PROBLEM MUST BE [illegible] STAGE [illegible]

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# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION
## Planning Sheet 7

## SKIRT AREA DESIGN #4

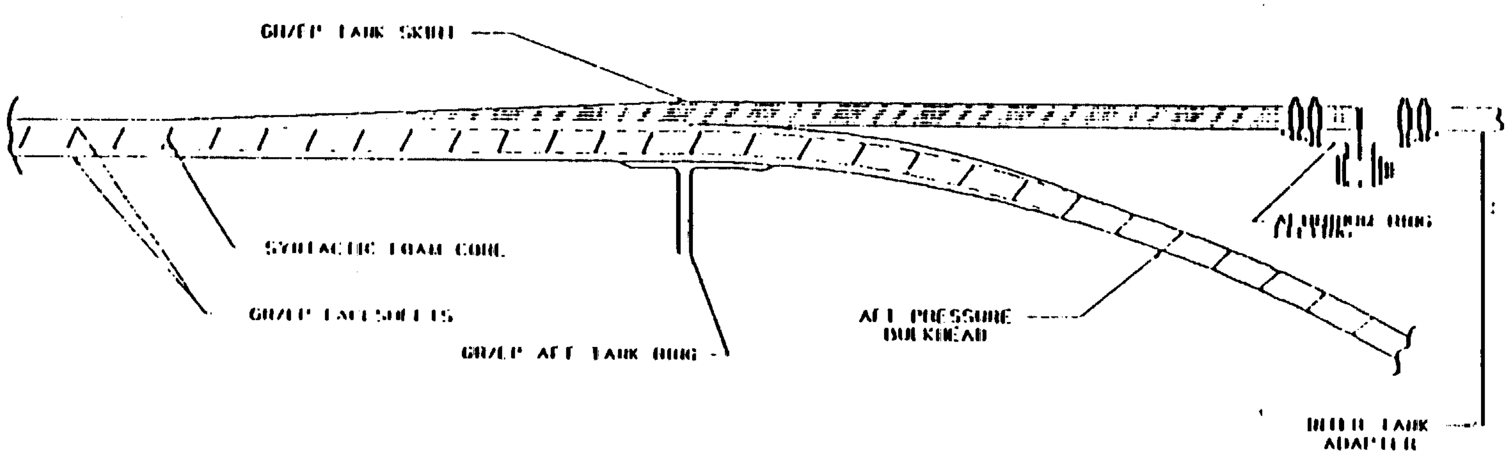


FIGURE 4, COMPOSITE PUMP-FED TANK DESIGN - AFT SKIRT REGION

ADVANTAGES

- EQUIVALENT STIFFNESS TO [illegible] TANK
- LIGHT WEIGHT SANDWICH TYPE CONSTRUCTION
- LESS DIFFICULT TO FABRICATE THAN A SIMILAR DESIGN USING HONEYCOMB CORE
- SKIRT/TANK SEPARATION LESS LIKELY TO OCCUR

DISADVANTAGES

- TANK-SKIRT TO TANK LAYUP REQUIRES SPECIAL TOOLING
- CORE MATERIAL WEIGHT WOULD BE GREATER THAN A HONEYCOMB MATERIAL
- AREA AROUND TANK RING WOULD BE DIFFICULT TO SEAL FOR A LOX TANK DESIGN

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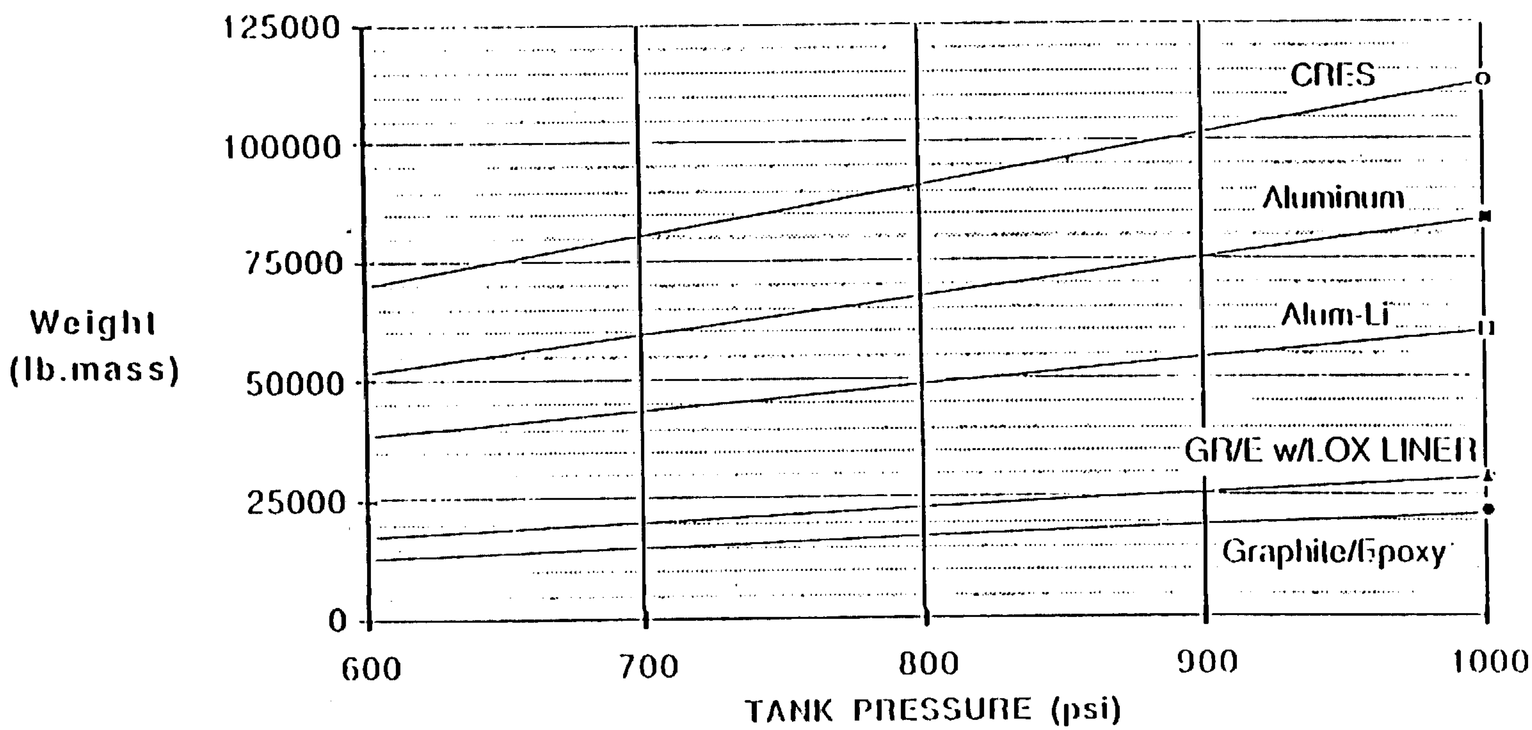
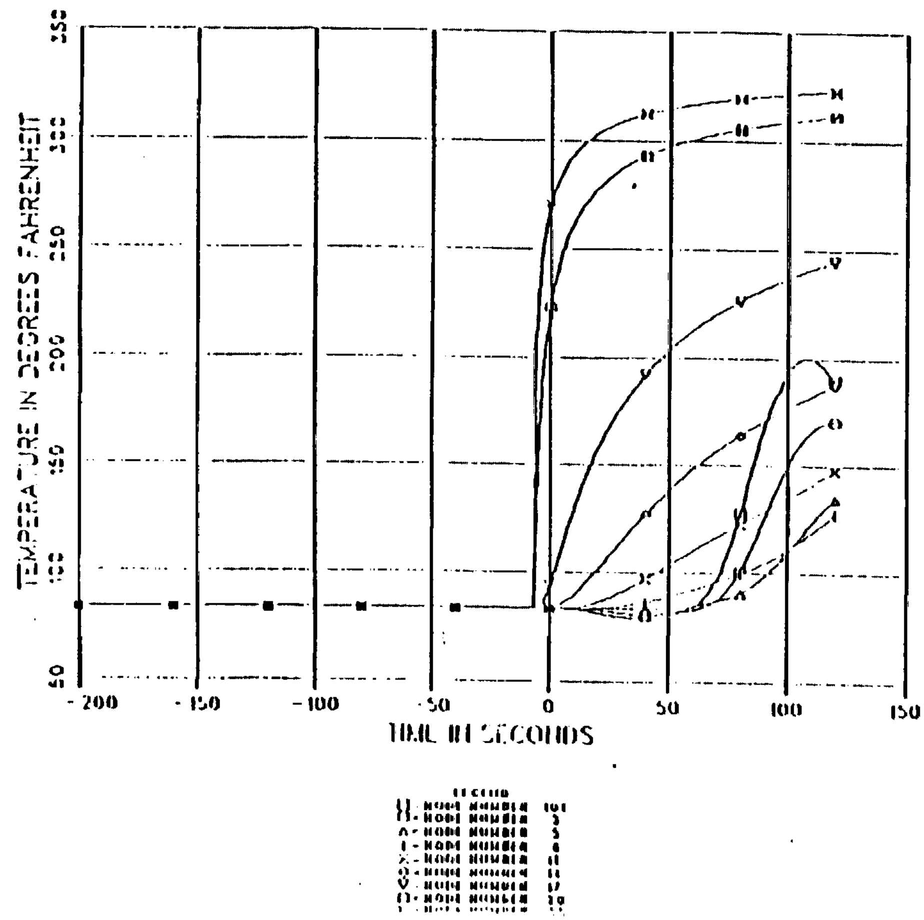
# TANK WEIGHT vs. TANK PRESSURE

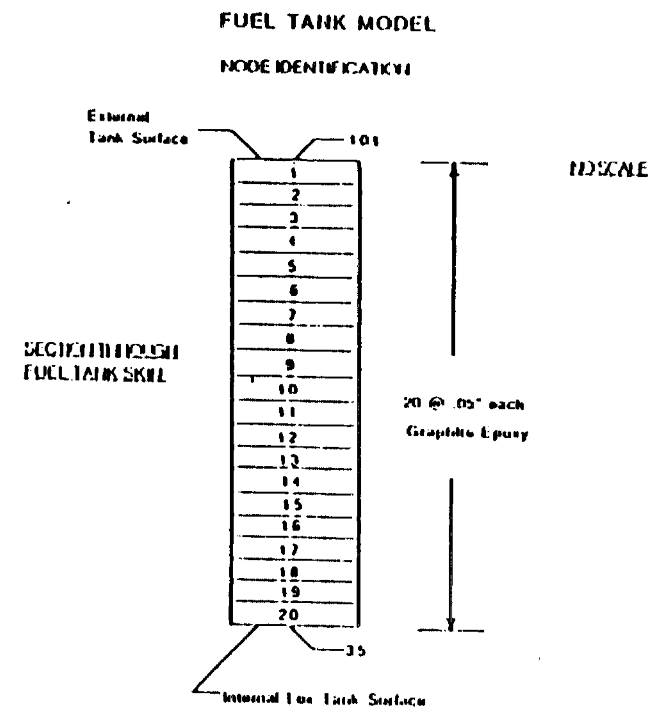



TANK VOLUME = 6597 (cu.ft.)

TKS 1/26/88

# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION
# HI-PRESSURE RP1 THERMAL HEATING PROFILE

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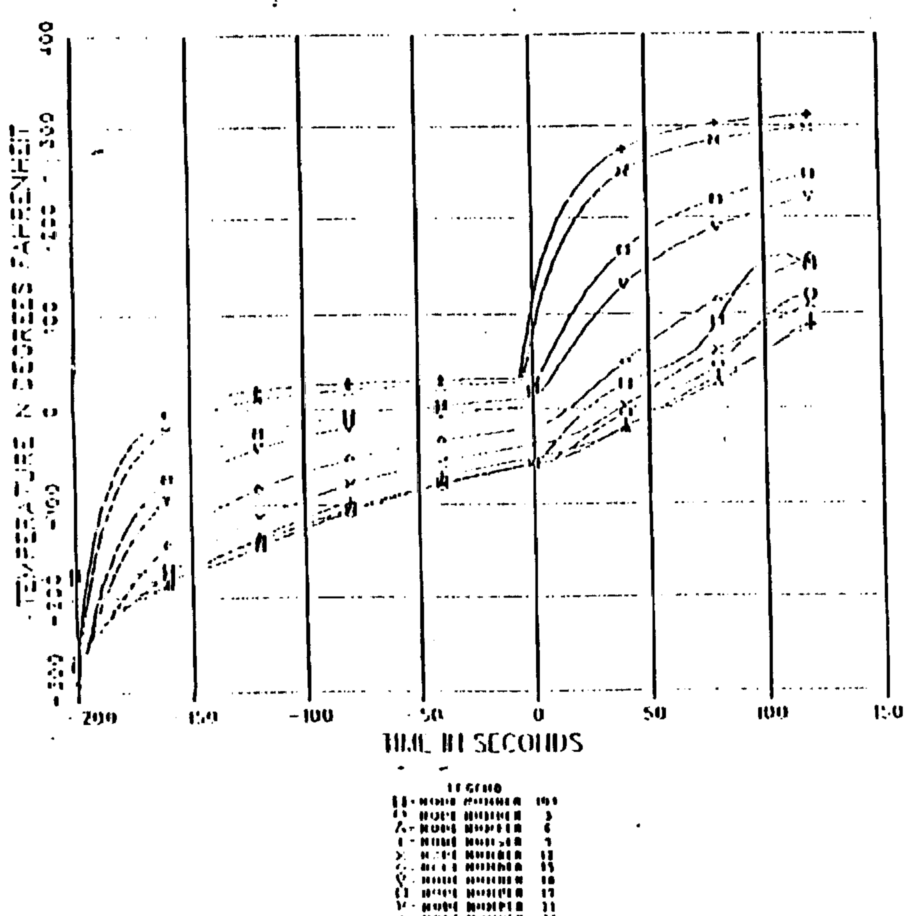
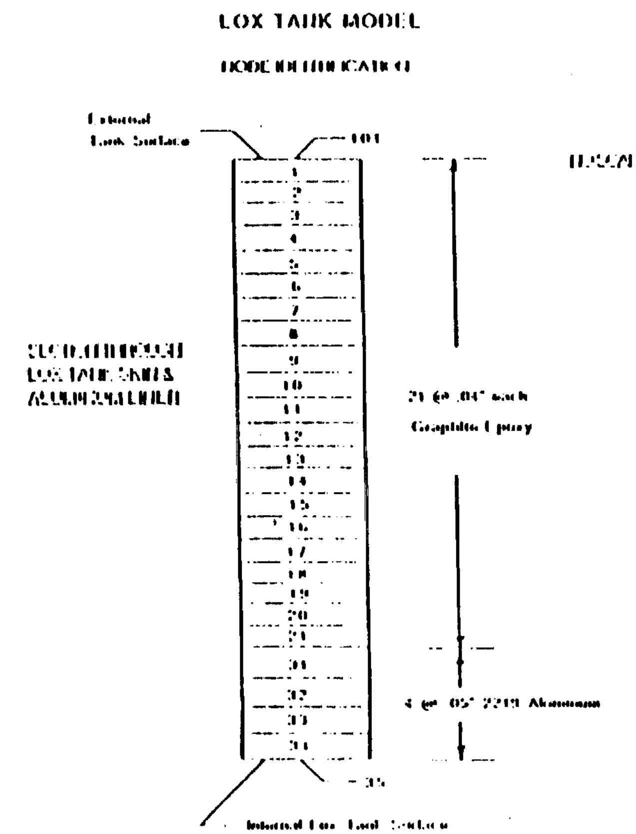
# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION
# HI-PRESSURE LOX THERMAL HEATING PROFILE

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# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION
## Lox Incompatiblity Problem

I. AL-LI & GRAPHITE/EPOXY HYBRID TANK (PRESSURE-FED)

THE AL-LI LINER WILL BE 25% LOAD SHARING TO HELP ENSURE THAT THE TANK WILL NOT LEAK DURING FLIGHT ONLY IF THE TANK PASSES THE INITIAL PRESSURE TEST BEFORE THE GRAPHITE/EPOXY IS OVERWRAPPED.

ADVANTAGES
1. SAFEST LIGHT WEIGHT ALTERNATIVE.

DISADVANTAGES
1. IF LOX WERE TO COME IN CONTACT WITH GR/EPOXY A CATASTROPHIC FAILURE WOULD OCCUR.

II. AL-LI TANK (PRESSURE-FED & PUMP-FED)

ADVANTAGES
1. LOX IS COMPATIBLE WITH ALUMINUM-LITHIUM.
2. FEASIBLE FOR PUMP-FED LOX TANK.

DISADVANTAGES
1. TWICE AS HEAVY AS GR/E w/AL-LI PRESSURE-FED TANK.

III. AL-LI,GR/E & HONEYCOMB SANDWICH (PUMP-FED)

ADVANTAGES
1. SLIGHT WEIGHT SAVINGS.

DISADVANTAGES
1. NOT FEASIBLE WITH LOX DUE TO RISK AND MANUFACTURING DIFFICULTIES.

7A

# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION

## Comparison Matrix

| PRESSURE FED | CONFIGURATION / PROPELLANT | MATERIAL: AL-LI | MATERIAL: GR/EPOXY | TANK CONSTRUCTION: STRETCH FORMED | TANK CONSTRUCTION: FILAMENT WOUND | TANK CONSTRUCTION: SANDWICH | TANK CONSTRUCTION: WAFFLE | TANK CONSTRUCTION: ISOGRID | TANK CONSTRUCTION: SKIN STRINGER | TANK CONSTRUCTION: RING FRAMES | TANK LINER MATERIAL: AL/LI | TANK LINER MATERIAL: NON METALLIC | TANK LINER MATERIAL: INVAR | TANK LINER MATERIAL: KEL F | TANK LINER MATERIAL: NONE | TANK LINER CONSTR: RIGID INNER SHELL | TANK LINER CONSTR: THIN LAMINATE | TANK LINER CONSTR: LOAD SHARING | INSULATION: PVC FOAM | INSULATION: POLYURETHANE | INSULATION: NONE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COMPOSITE | LOX | X | X | X | X | | | | | | X | | | | | X | | X | X | | |
| | RP1 | | X | | X | | | | | | | | | | X | | | | | | X |
| METALLIC | LOX | X | | X | | | | X | | X | | | | | X | | | | X | | |
| | RP1 | X | | X | | | X | | | X | | | | | X | | | | | | X |

NOTE: ALL PRESSURE FED TANKS WILL BE A MONOCOQUE STRUCTURE.



(V)

# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION
## Comparison Matrix

| | CONFIGURATION / PROPELLANT | MATERIAL: AL-LI | MATERIAL: GR/EPOXY | TANK CONSTRUCTION: STRETCH FORMED | TANK CONSTRUCTION: FILAMENT WOUND | TANK CONSTRUCTION: SANDWICH | TANK CONSTRUCTION: WAFFLE | TANK CONSTRUCTION: ISOGRID | TANK CONSTRUCTION: SKIN STRINGER | TANK CONSTRUCTION: RING FRAMES | TANK CONSTRUCTION: MONOCOQUE | TANK LINER MATERIAL: AL/LI | TANK LINER MATERIAL: NON METALLIC | TANK LINER MATERIAL: INVAR | TANK LINER MATERIAL: NONE | TANK LINER CONST.: RIGID INNER SHELL | TANK LINER CONST.: THIN LAMINATE | TANK LINER CONST.: LOAD SHARING | INSULATION: PVC FOAM | INSULATION: POLYURETHANE | INSULATION: NONE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COMPOSITE | LOX | X | X | X | X | X | | | | | | X | | | | X | | X | X | | |
| COMPOSITE | RP1 | | X | | X | X | | | | | | | | | X | | | | | | X |
| COMPOSITE | $LH_2$ | | X | | X | X | | | | X | | | X or X | | | | X | | | X | |
| METALLIC | LOX (-297°F) | X | | X | | | | X | X | X | | | | | X | | | | X | | |
| METALLIC | RP1 (70°F) | X | | X | | | X | | X | X | | | | | X | | | | | | X |
| METALLIC | $LH_2$ (-423°F) | X | | X | | | | X | X | X | | | | | X | | | | | X | |

PUMP FED

7A

# TRADE STUDY 1.12 TANK CONFIGURATION SELECTION

## 3.0 Summary of Results

### CONCLUSIONS:

FOR A PUMP-FED LOX TANK, AN ALL METALLIC TANK DESIGN WOULD HAVE THE LOWEST RISK VERSES AN ADVANCED TECHNOLOGY COMPOSITE TANK DESIGN. A COMPOSITE DESIGN WOULD OFFER ONLY A SLIGHT WEIGHT ADVANTAGE OVER THE METALLIC DESIGN DUE TO REDUCED ALLOWABLES CAUSED BY THE MANUFACTURE OF LARGE TANK STRUCTURES USING THIN LAMINATES AND A METALLIC LINER. HOWEVER, A COMPOSITE DESIGN WOULD BE PREFERED FOR THE RP-1 TANK, DUE TO A METALLIC LINER NOT BEING REQUIED.

IF A PRESSURE-FED LRB IS PROPOSED, THAN THE HIGHEST PERFORMANCE MAY BE SEEN BY A TANK DESIGN INCORPORATING AN ADVANCED COMPOSITE, SUCH AS GRAPHITE/EPOXY FILAMENT WOUND TOW. USING FILAMENT WINDING TECHNOLOGY FROM SOLID ROCKET MOTOR CASES, AN ALL COMPOSITE TANK FOR THE RP-1 PROPELLANT WOULD BE POSSIBLE. FIBER-OVERWRAPPED METALLIC PRESSURE VESSEL TECHNOLOGY COULD ALSO BE APPLIED TO THE DESIGN OF THE LOX TANK, PROVIDING LOW RISK LOX COMPATIBILITY.

### RECOMMENDATIONS:

-CONTINUE RESEARCH, DESIGN AND ANALYSIS OF FILAMENT WOUND TANK STRUCTURES FOR THE LRB (BOTH PUMP AND PRESSURE-FED).

Reference 1 1987 JANNAF COMPOSITE MOTOR CASE SUBCOMMITTE MEETING J.D. Erickson & J.A. Yorgason, Morton Thiokol, Inc., Wasatch Operations, Brigham City, UT.,"GRAPHITE EPOXY PRESSURE VESSEL DOME REINFORCEMENT STUDY", February 17-19,1987, pp.11-23.

# COMPOSITE TANK RISKS

LRB

I. LINER REQUIRED

- LOX COMPATIBILITY, i.e. GR/EPOXY IN CONTACT WITH LOX EXPLOSIVE
- LINER THICKNESS GREATER THAN NORMAL TO RESIST BUCKING DUE TO HIGH FIBER OVERWRAP TENSILE STRESSES PRESENT IN AN EMPTY, UNPRESSURIZED TANK.

II. HIGH TEMPERATURE CAPABILITY

- HIGH He GAS PRESSURIZATION TEMPERATURES (~800R) DICTATE USING SLIGHTLY REDUCED COMPOSITE STRENGTH ALLOWABLES ON TOP OF HOT/WET CONDITION ALLOWABLES.
- RESIN SYSTEMS EXIST THAT HANDLE HIGH TEMPERATURES AND OTHER SYSTEMS HANDLE CRYOGENIC TEMPERATURES. HOWEVER, RESEARCH IS CONTINUING IN SEARCHING FOR AN OPTIMUM RESIN SYSTEM TO HANDLE THE WIDE TEMPERATURE RANGE ON TOP OF BEING COMPATIBLE WITH SALT WATER FOR REUSABILITY PURPOSES.

III. EXISTING TECHNOLOGY

- SMALL COMPOSITE-METAL LINED STORAGE BOTTLES ARE MADE BY STRUCTURAL COMPOSITE INDUSTRIES TODAY, BUT THE RISK WILL BE IN SCALING THESE DESIGNS INTO MUCH LARGER TANKS FOR 'LRB'.

IV. FURTHER STUDY AND ANALYSIS REQUIRED

- SEVERAL 1988 GDSS IRADS ARE PRESENTLY IN WORK

## UPDATE ON T.S. 1.12 TANK CONFIGURATION SELECTION

At the midterm program review we recommended composite tanks to minimize weight on the pressure fed LRB concept. We acknowledged the risk in this new technology area particularly an aluminum liner in the LOX tank. In his memo 3/14/88, "Results of LRB Configuration Review", MSFC/Larry Wear advised us that "...the selection of composite tanks for cryogenic propellants is inconsistent with design goals of maximum flight safety."

Therefore we have adapted as a low risk baseline lithium-aluminum for pump fed tanks and 2219 aluminum for pressure fed. The difference is due to the approximately 1 inch thick walls for pressure fed. Most Al-Li work to date has been on 1/4 inch thickness or less, with good results in LOX compatibility, VPPA weldability, etc. On thicker sections there is less information. Problems have occurred with weak transverse properties in thicker sections.

Using GDSS IRAD funds, we are continuing to explore graphite epoxy propellant tanks for LOX, RP-1, and LH2.

LIQUID ROCKET BOOSTER
TRADE STUDY ERB
FEBRUARY 11, 1988

TRADE STUDY 1.14
FINAL ERB

# PRESSURE FED
# PRESSURIZATION SYSTEM SELECTION

STUDY LEADER: BILL PIERCE

SYSTEMS ENGINEER: MIKE VACCARO

**GENERAL DYNAMICS**
*Space Systems Division*

# TRADE STUDY 1.14

## PRESSURE FED - PRESSURIZATION SYSTEM SELECTION

## PLANNING SHEET 1

### OBJECTIVE:

SELECT THE OPTIMUM PRESSURIZATION SYSTEM FOR A PRESSURE FED LIQUID ROCKET BOOSTER

### GROUNDRULES/ASSUMPTIONS/GUIDELINES:

- PRESSURANT COMPATIBLE WITH PROPELLANT
- HELIUM STORAGE BOTTLE PRESSURE 4000 PSIA
- COLD HELIUM STORAGE BOTTLE TEMPERATURE 150 DEGREES R
- TANK PRESSURE 700 PSIA
- MAXIMUM ULLAGE TEMPERATURE 800 DEGREES R
- HELIUM STORAGE SAFETY FACTOR 1.5
- MAIN PROPELLANT LO2/RP-1

# 1.14 PRESSURE FED - PRESSURIZATION SYSTEM SELECTION
## Planning Sheet 2

### REQUIREMENTS:

- PRESSURIZATION SYSTEM SHALL BE SAFE AND RELIABLE (MAN RATED)
- PRESSURIZATION SYSTEM SHALL SUPPLY THE REQUIRED VOLUME OF PRESSURANT AT THE REQUIRED TANK PRESSURE FOR EACH PROPELLANT.
- PRESSURIZATION SYSTEM SHALL MAINTAIN LAUNCH READINESS DURING A 24 HOUR HOLD

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### CONSTRAINTS:

- NO PUMP

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# 1.14 PRESSURE FED - PRESSURIZATION SYSTEM SELECTION
## Planning Sheet 4
## Trade Tree

### PRESSURIZATION SYSTEM OPTIONS

**(A)**
AMBIENT He BOTH TANKS.

**(B)**
COLD He BOTH TANKS.
HEATED WITH LO2/RP GG.

**(C)**
COLD He BOTH TANKS.
HEATED WITH LO2/RP GG.
He STORAGE BOTTLE
HEATED WITH He COIL.

**(D)**
COLD He BOTH TANKS.
HEATED WITH LO2/RP GG.
He STORAGE BOTTLE
HEATED WITH CASCADE.

**(E)**
COLD He BOTH TANKS.
HEATED WITH ENGINE Hx.

**(F)**
LN2 BOTH TANKS.
HEATED WITH LO2/RP GG.

**(G)**
COLD He OXID TANK.
LN2 FUEL TANK.
HEATED WITH LO2/RP GG.

**(H)**
COLD He OXID TANK.
LH2 FUEL TANK.
HEATED WITH LO2/RP GG.

**(J)**
LO2 OXID TANK.
COMBUSTION PRODUCTS
FUEL TANK.
HEATED WITH HIGH
PRESS LO2/LH2 GG.

**(K)**
COLD He OXID TANK.
COMBUSTION PRODUCTS
FUEL TANK.
HEATED WITH HIGH
PRESSURE LO2/LH2 GG.

**(L)**
COLD He OXID TANK.
H2H4 DECOMPOSITION
PRODUCTS FUEL TANK.
HEATED WITH N2H4 DECOMP.

**(M)**
He/H2/O2 MIXTURE
BOTH TANKS.
HEATED BY CATALYTIC
REACTION.

# 1.14 PRESSURE FED - PRESSURIZATION SYSTEM SELECTION

## SUMMARY OF PRESSURIZATION SYSTEM OPTIONS

| | A<br>Ambient Helium (He) | B<br>Cold He Heated With LO2/RP-1 Gas Generator | C<br>Cold He Heated With LO2/RP-1 Gas Generator and Hot He Coil passing through He storage bottle | D<br>Cold He heated with LO2/RP-1 Gas Generator and Three Storage Bottle Cascade |
|---|---|---|---|---|
| Pressurant<br>Storage Bottle | 18,529 He<br>60,690 (Five 14.9 Dia. He) | 11,725 He<br>14,600 (14.9 Dia. He) | 6,846 He<br>8,707 (12.4 Dia. He) | 6,069 He<br>7,558 (11.7 Dia. He)<br>667 (4.6 Dia. He)<br>168 (2.6 Dia. He) |
| Components<br>Main Propellant | | 5,000<br>5,954 | 8,525<br>5,874 | 5,398<br>6,431 |
| Total Weight | 79,219 Lbs. | 37,279 Lbs. | 29,952 Lbs. | 26,291 Lbs. |
| Advantages | • Proven technology<br>• Simple | • Proven technology | • Same as B, but less residual He makes it lighter | • Same as B, but less residual He makes it lighter. |
| Disadvantages | • Very Heavy<br>• Very large volume | • Heavy | • Approximately 600 ft of 3 inch tubing in storage bottle. | • Complex with three different storage bottles. |
| Safety and Reliability | • Very High | • High | • High | • Medium |

# 1.14 PRESSURE FED - PRESSURIZATION SYSTEM SELECTION

## SUMMARY OF PRESSURIZATION SYSTEM OPTIONS

| | E<br>Cold He heated with Heat Exchanger which is part of Engine Cooling System | F<br>LN2 heated with LO2/RP-1 Gas Generator | G<br>LN2 to pressurize fuel tank and Cold He to pressurize Oxidizer Tank; Both heated with LO2/RP-1 Gas Generator | H<br>LH2 to pressurize fuel tank and Cold He to pressurize Oxidizer Tank; Both heated with LO2/RP-1 Gas Generator |
|---|---|---|---|---|
| Pressurant<br>Storage Bottle. | 11,725 He<br>14,600 (14.9 Dia. He) | 44,978 He & LN2<br>5,750 (10.7 Dia. He)<br>738 (11.5 Dia. LN2) | 23,679 He & LN2<br>11,218 (13.6 Dia. He)<br>337 (8.2 Dia. LN2) | 9,832 He & LH2<br>10,885 (13.5 Dia. He)<br>290 (7.7 Dia. LH2) |
| Components<br>Main Propellant | *397<br>2,142 | 10,601<br>11,967 | 6,857<br>8,116 | 6,166<br>7,346 |
| Total Weight | 28,864 Lbs. | 74,034 Lbs. | 50,207 Lbs. | 34,519 Lbs. |
| Advantages | • Light weight | • Proven Technology | • Proven Technology | • Proven Technology |
| Disadvantages | • Makes engine more complex and possibly less reliable | • Very heavy | • Very heavy | • More complex than B<br>• LH2 on board |
| Safety and Reliability | • Medium | • High | • High | • Medium |

*Net increase from weight of ablative thrust chamber

# 1.14 PRESSURE FED - PRESSURIZATION SYSTEM SELECTION

## SUMMARY OF PRESSURIZATION SYSTEM OPTIONS

| | J<br>High Press LO2/LH2 Gas Generator Combustion Products to Pressurize Fuel Tank and to Heat LO2 to Pressurize Oxidizer Tank | K<br>High Press LO2/LH2 Gas Generator Combustion Products to Pressurize Fuel Tank and to Heat Cold He to Pressurize Oxidizer Tank | L<br>N2H4 Decomposition Products to pressurize Fuel Tank and to Heat Cold He to Pressurize Oxidizer Tank | M<br>Cold He Mixed with Small Amounts of H2 and O2 Heated by Catalytic Reaction |
|---|---|---|---|---|
| Pressurant Storage Bottle | 44,130 He,LO2 & LH2<br>8,060 (11.9 Dia. He)<br>1,771 (11.4 Dia. LH2)<br>1,111 (10.0 Dia. LO2) | 13,299 He,LO2 & LH2<br>13,261 (14.3 Dia. He)<br>746 (8.3 Dia. LH2)<br>70 (3.3 Dia. LO2) | 17,125 He & N2H4<br>9,570 (12.9 Dia. He)<br>309 (6.6 DIA N2H4) | 8,216 He/H2/O2 Mix<br>11,740 (13.9 Dia. Mix)<br>4,701 (9.9 Dia. Mix) |
| Components<br>Main Propellant | 2,792 | 1,082 | 5,289<br>- 1,256 | 400 |
| Total Weight | 84,573 Lbs. | 38,913 Lbs. | 31,037 Lbs. | 25,057 Lbs. |
| Advantages | | • Lighter than B | • Proven Technology<br>• Light weight | • Lightest system<br>• Simple |
| Disadvantages | • Very heavy<br>• Complex with three different storage bottles<br>• LH2 on board | • Complex with three different storage bottles<br>• LH2 on board | • Requires 10,000 pounds of N2H4 which is toxic | • Needs development for LRB operating conditions |
| Safety and Reliability | • Low | • Low | • Medium | • High |

# TRIDYNE

- A GASEOUS MIXTURE ($O_2/H_2$ + $N_2$ OR He DILUENT) PROVIDING A CATALYTICALLY HEATED GAS FOR THRUSTERS AND PRESSURIZATION
- MIXTURES ARE SAFELY STORABLE IN CONVENTIONAL PRESSURE VESSEL
- USES SIMPLE BASIC STRUCTURE OF A COLD GAS SYSTEM
- CATALYST CHARACTERISTICS PROVIDE PREDICTABLE REACTION FOR A GIVEN GAS MIXTURE
- TECHNOLOGY BASE IS WELL ESTABLISHED
- CURRENTLY BASELINED FOR MX STAGE IV PRESSURIZATION SUBSYSTEM

235-535

Rockwell International
Rocketdyne Division

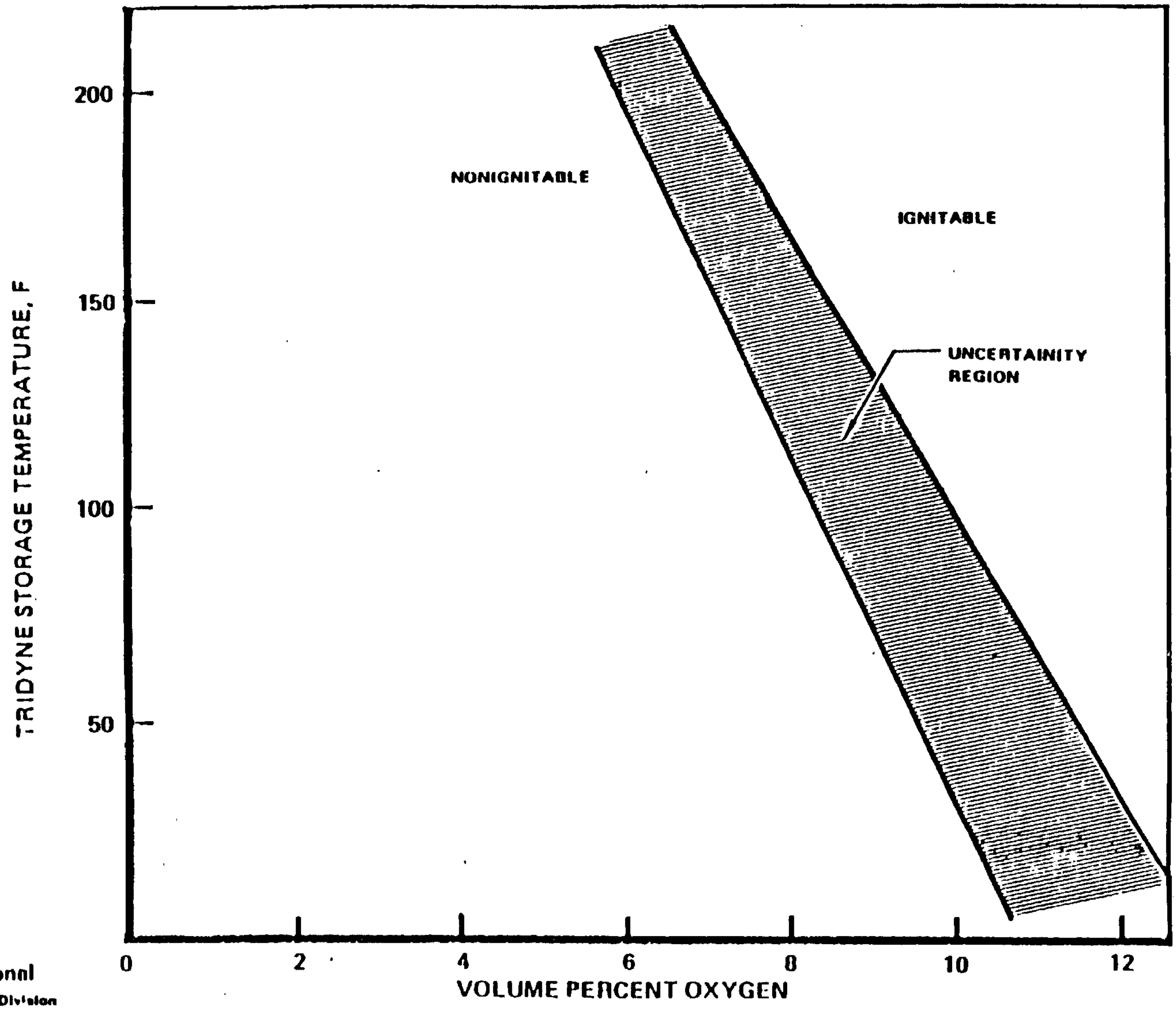
# ROCKETDYNE TRIDYNE EXPERIENCE AND APPLICATIONS INVESTIGATIONS

| TYPE EFFORT | YEAR | SPONSORING AGENCY |
|---|---|---|
| GASEOUS-BLOWDOWN PROPULSION | 1964 | IR&D |
| TANK PRESSURIZATION SYSTEMS | 1966 | AFRPL, AF04(611)-11383 |
| ATTITUDE CONTROL THRUSTERS | 1970 | NASA, NAS7-719 |
| GUN BREECH SCAVENGER SYSTEMS | 1973 | ARMY, DAAA22-74-C-0107 |
| GUN BREECH SCAVENGER SYSTEMS | 1975 | ARMY, DAAA22-75-C-0158 |
| MINUTEMAN II TRIDYNE VCS DESIGN | 1977 | ROCKETDYNE |
| IGNITABILITY AND ADIABATIC COMPRESSION TESTS | 1977 | IR&D |
| LIGHT-WEIGHT ADVANCED POST-BOOST VEHICLE PROPULSION FEED SYSTEM | 1977 | AFRPL, F04611-77-C-0068 |

285-525B

Rockwell International
Rocketdyne Division

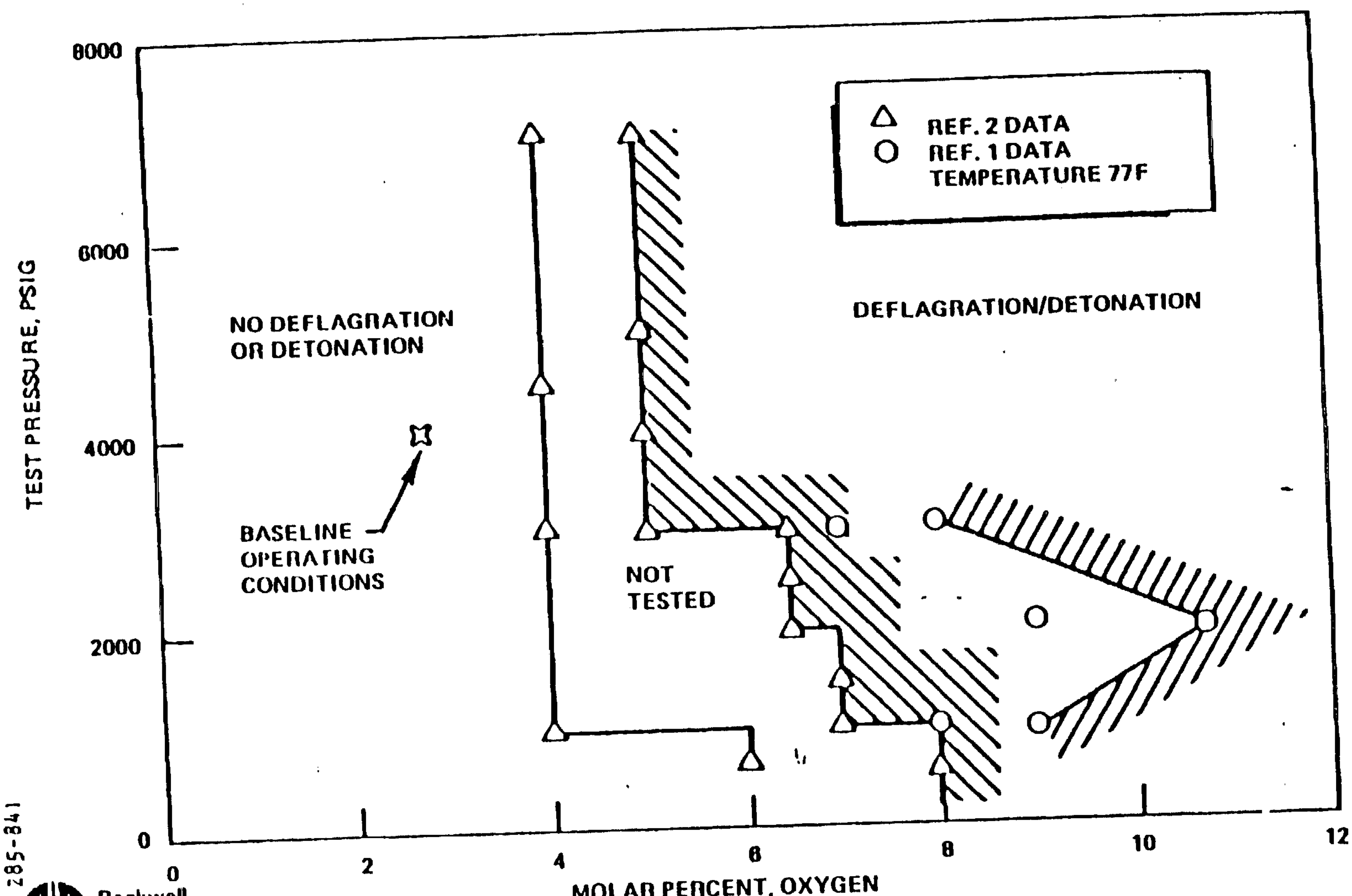
# CONCENTRATION TEMPERATURE STABILITY FOR HELIUM TRIDYNE AT 2000 PSIA




285-835

Rockwell International
Rocketdyne Division

# He-TRIDYNE CONCENTRATION-PRESSURE IGNITABILITY LIMITS AT AMBIENT TEMPERATURE

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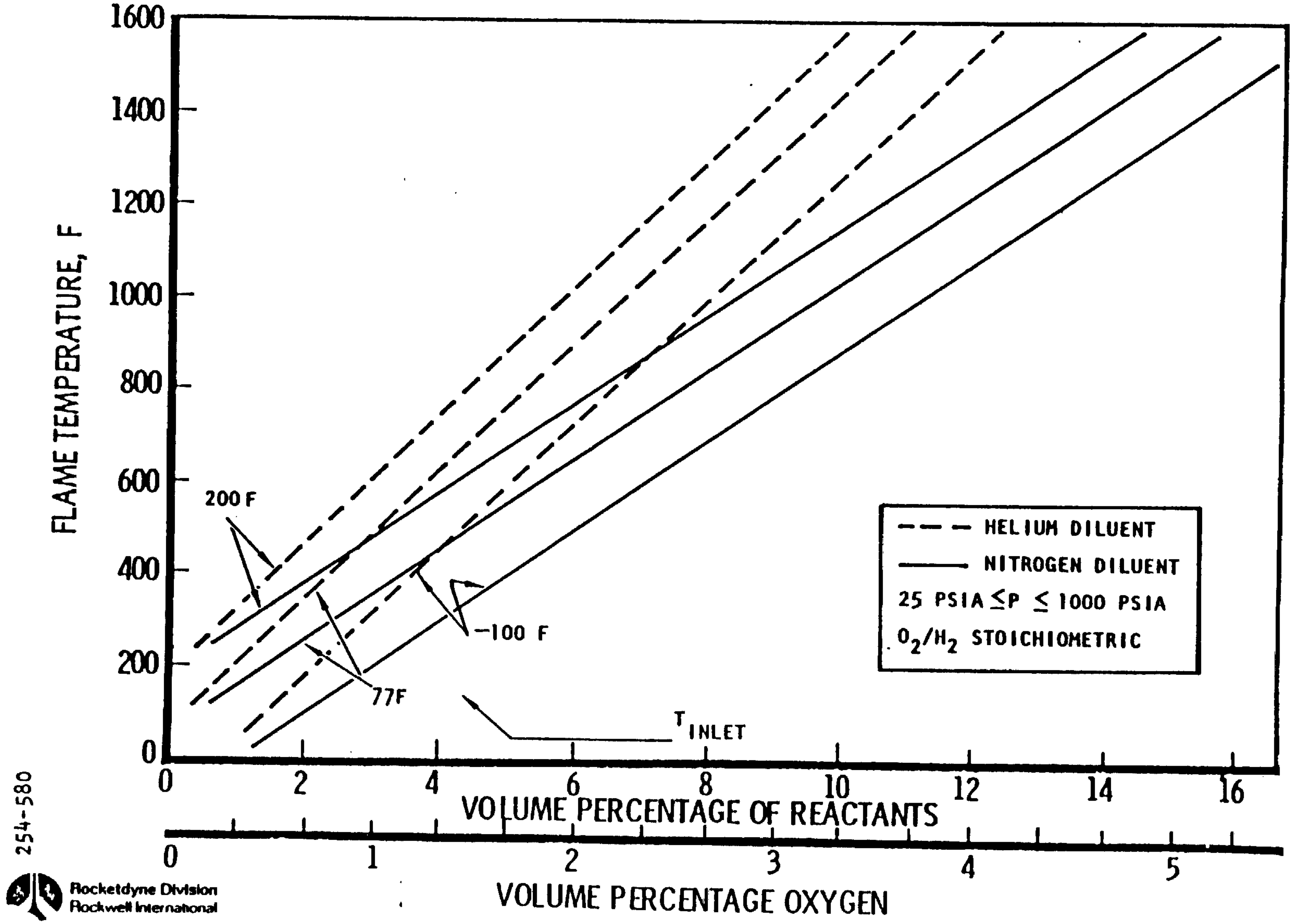
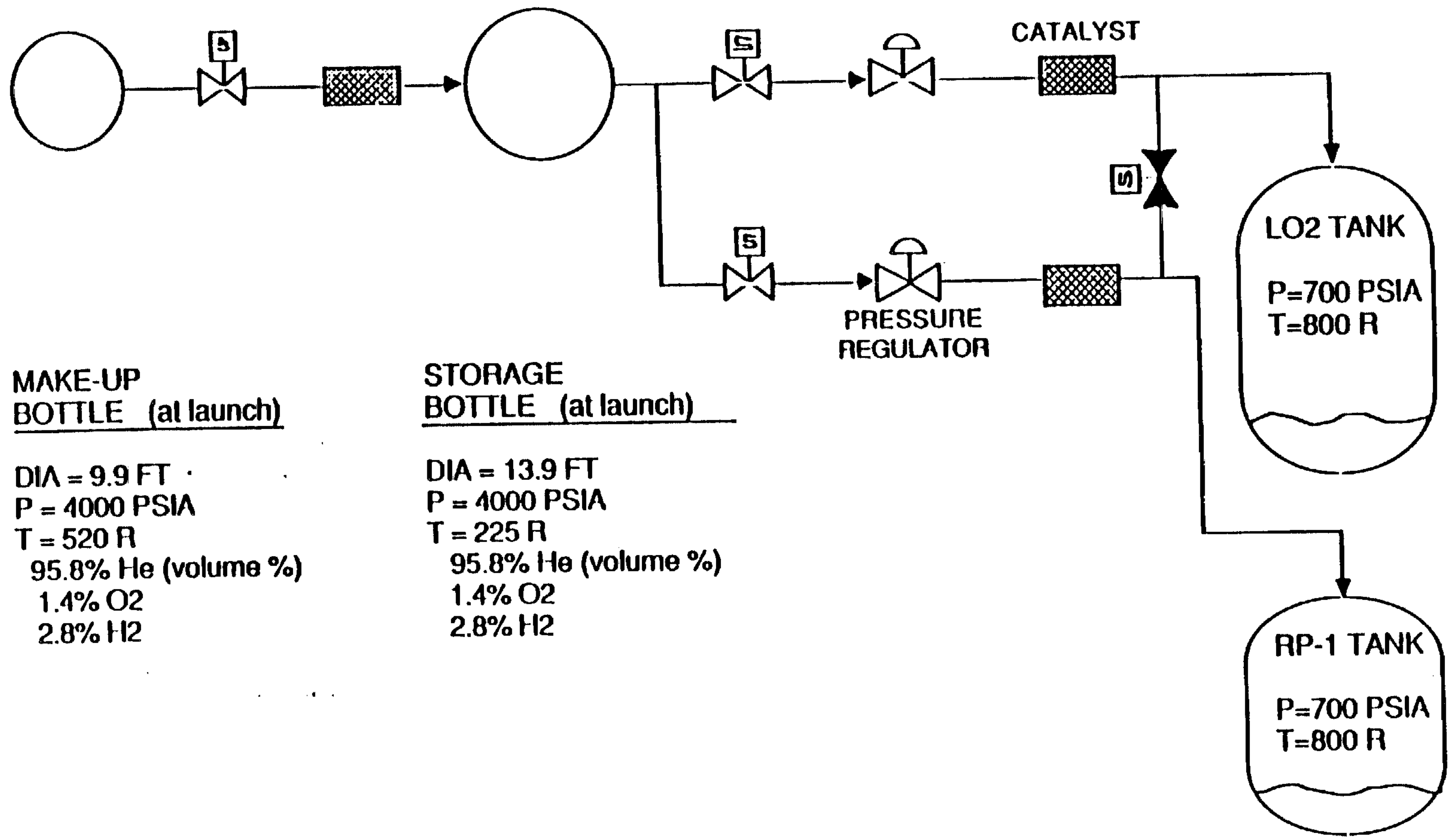
Rocketdyne Division

# TRIDYNE COMPOSITION



# SELECTED PRESSURIZATION SYSTEM
# PRESSURANT HEATED BY CATALYTIC REACTION

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# 1.14 PRESSURE FED - PRESSURIZATION SYSTEM SELECTION

## SUMMARY AND CONCLUSIONS

- The $H_2/O_2$ catalytic reaction system (option M) was selected as potentially the best pressurization system for the Pressure Fed Engine.
  - Lightest System
  - Less impact on other systems
  - Fewer Pressurization lines than other systems
  - No overboard dump.

- Development Requirements for the $H_2/O_2$ catalytic reaction system
  - Show that the system will operate properly for the pressure, temperature and flow range expected for LRB.
  - Determine the nonignitable region (volume percent of $H_2$ and $O_2$ in the mixture) for LRB operating conditions.
  - Prove that ice crystals, which may form in the $LO_2$ tank, will not cause a problem.

LIQUID ROCKET BOOSTER
TRADE STUDY ERB
FEBRUARY 1, 1988

TRADE STUDY 1.8
FINAL ERB

# PUMPFED ENGINE TYPE/PERFORMANCE SELECTION

STUDY LEADER: TINA NGUYEN/GOPAL MEHTA

SYSTEMS ENGINEER: MIKE VACCARO

**GENERAL DYNAMICS**
*Space Systems Division*

# 1.8 PUMPFED ENGINE TYPE/PERFORMANCE SELECTION

## OBJECTIVES:

- PROVIDE PERFORMANCE DATA FOR ALL ENGINE CANDIDATES
  - VALIDATE DATA USED IN INITIAL TRADES AND ANALYSES
  - PROVIDE UPDATED DATA WHERE NECESSARY, ESPECIALLY FOR SELECTED ENGINES
- PROVIDE QUALITATIVE EVALUATION FOR ALL ENGINE CONCEPTS

# 1.8 PUMPFED ENGINE TYPE/PERFORMANCE SELECTION

## GROUNDRULES/ASSUMPTIONS/GUIDELINES:

- CHAMBER PRESSURES, MIXTURE RATIOS & EFFICIENCIES PROPOSED IN STME & STBE WILL BE USED.
- UPDATED ENGINE DATA ARE TO BE VERIFIED AGAINST STME & STBE POINT DESIGNS FROM PRATT & WHITNEY, ROCKETDYNE AND AEROJET.
- ONE-DIMENSIONAL EQUILIBRIUM CODE WITH TYPICAL CHAMBER PRESSURE AND ENGINE EFFICIENCIES WILL BE USED TO GENERATE ENGINE PERFORMANCE WHERE NO DATA ARE AVAILABLE.
- PRATT & WHITNEY'S PARAMETRIC EQUATIONS FROM HYDROCARBON ENGINE STUDY WERE USED FOR INITIAL TRADES. (ONLY AVAILABLE DATA)
- DATA WILL EMPHASIZE ON DOWNSELECTED CONCEPTS AS OF 1/15/88, WHICH INCLUDE SSME-35, F-1, NEW LO2/LH2 AND NEW LO2/RP1ENGINES. ALSO, BOTH REUSABLE AND EXPENDABLE MODES WILL BE CONSIDERED FOR THESE SELECTED ENGINES.

# 1.8 PUMPFED ENGINE TYPE/PERFORMANCE SELECTION

## Cost Assumptions

- GD COST MODEL FOR DDT&E AND PRODUCTION COST, USED IN ALS AND STAS, ASSUMING LOW COST EXPENDABLE PROPULSION STUDY RESULTS
- 93% LEARNING CURVE; 91.5% RATE CURVE
- 25 MISSION LIFE FOR ALL WATER RECOVERABLE ENGINES
- OVERHAUL COST BETWEEN FLIGHTS FOR WATER RECOVERY IN TERMS OF FIRST UNIT COST ASSUMING 1 ENGINE OVERHAUL/YR IS

  30% FOR SSME-35 AND F-1;    25% FOR NEW GG ENGINES

# 1.8 PUMPFED ENGINE TYPE/PERFORMANCE SELECTION

## REQUIREMENTS:

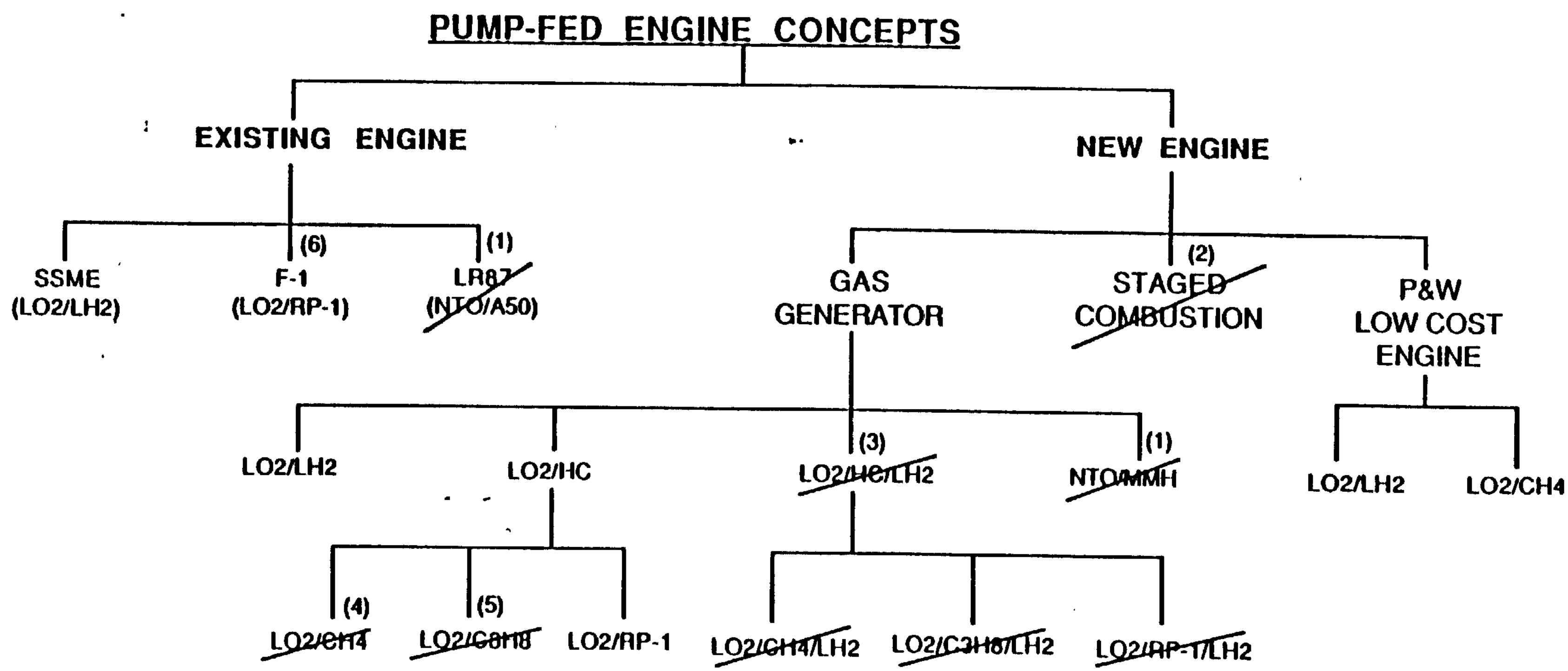
1. 70 KLB PAYLOAD TO 150 NM ORBIT, 28.5 DEG INCLINATION, WITH ORBITER SSME'S LIMITED TO 100% PL
2. 59 KLB PAYLOAD TO 150 NM ORBIT, 28.5 DEG INCLINATION, WITH ORBITER SSME'S LIMITED TO 104% PL
3. SATISFY STS TRAJECTORY REQUIREMENTS (IE. LIFTOFF T/W, MAX G, MAX Q, ETC.)
4. ENGINE/VEHICLE INTERFACE REQUIREMENTS - TBD

## CONSTRAINTS:

- EXISTING ENGINE CONCEPT WILL ONLY CONSIDER ENGINES WITH THRUST SIZE LARGER THAN 300KLB. ALSO, ONLY PROVEN CAPABILITIES OF THESE ENGINES WILL BE CONSIDERED.
- EFFECT OF CONTROL AUTHORITY WILL NOT BE CONSIDERED
- ENGINE NOZZLE SIZE IS LIMITED BY DIMENSIONS OF FLAME TRENCH (EG. MAXIMUM NOZZLE EXIT DIAMETER IS 90IN FOR 4 ENGINES/LRB CONFIGURATION)
- DATA BASE FOR NEW ENGINES WILL BE RESTRICTED TO:
  - STME & STBE STUDIES (POINT DESIGN)
  - LOW COST EXPENDABLE ENGINE STUDIES
  - HYDROCARBON ENGINE STUDIES (PARAMETRIC EQUATIONS BY PRATT & WHITNEY)
  - NEW IMPROVED ENGINE PARAMETRIC EQUATIONS FOR ALS FROM PRATT & WHITNEY
  - ONE-DIMENSIONAL EQUILIBRIUM (ODE) CODE WITH TYPICAL EFFICIENCIES FOR NTO/MMH

# 1.8 PUMP-FED ENGINE TYPE/PERFORMANCE SELECTION

## Trade Tree




- RESULTS OF INITIAL TRADES/ANALYSES:

(1) ELIMINATED ON BASIS OF SAFETY & ENVIRONMENTAL IMPACTS
(2) STAGED-COMBUSTION CYCLE WAS RANKED LOWER THAN GAS-GENERATOR CYCLE IN PREVIOUS STUDIES
(3) ELIMINATED ON BASIS OF HIGH COST, COMPLEXITY & TECHNICAL RISK ASSOCIATED WITH TRIPROPELLANTS
(4) ELIMINATED ON BASIS OF HIGH TECHNICAL RISK AS COMPARED TO LO2/RP1 AND LO2/LH2
(5) OFFERS NO MAJOR ADVANTAGES AS COMPARED TO LO2/CH4 AND LO2/RP1
(6) RECENTLY ELIMINATED ON BASIS OF HIGH RISK IN CONTROL AUTHORITY, REQUALIFICATION COST & SCHEDULE (1/28/88)

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# 1.8 PUMPFED ENGINE TYPE/PERFORMANCE SELECTION

## Existing Engine Evaluation

| CRITERIA | SSME-35 | F-1 | LR87-11 |
|---|---|---|---|
| PROPELLANT | LO2/LH2 | LO2/RP1 | NTO/A-50 |
| NO. OF ENGINE PER BOOSTER | 4 | 2 | 5 PAIRS |
| IGNITION COMPLEXITY | MEDIUM | HIGH | LOW |
| ENGINE OPERATIONAL COMPLEXITY | VERY HIGH | MEDIUM | LOW |
| THROTTLEABILITY | 65% TO 109% RPL | 1.25 TO 1.8MLB | PRESET THRUST ONLY |
| FLT PROVEN REUSABILITY | MAXIMUM OF 10 MISSIONS | NONE | NONE |
| LEAD TIME | 48 MONTHS | 48 MONTHS | 30 MONTHS |
| COST | HIGH RECURRING COST | MEDIUM RECURRING COST<br>$85M NON-RECURRING COST | LOW RECURRING COST |
| TECHNOLOGY RISK | LOW | MEDIUM | LOW |
| SCHEDULE RISK | LOW | HIGH | LOW |
| LRB CONTROL AUTHORITY | GOOD | MARGINAL | GOOD |

# 1.8 PUMPFED ENGINE TYPE/PERFORMANCE SELECTION

## Existing Engine: SSME-35

| | | | |
|---|---|---|---|
| • RPL | 65% | 100% | 109% |
| • SL THRUST, LB | 253.3K | 412.8K | 453.9K |
| • VAC THRUST, LB | 296.3K | 455.8K | 496.8K |
| • SL Isp, SEC | | 398.6 | 403.4 |
| • VAC Isp, SEC | | 440.1 | 441.5 |
| • Pc, PSIA | 1947 | 2995 | 3265 |
| • MR | | 6.0 | |
| • AREA RATIO | | 35 | |
| • D exit, IN | | 61 | |
| • LENGTH, IN | | 146 | |
| • WEIGHT, LB | (DRY) 6550 | (WET) 7090 | |
| • GIMBALLING | | ±11°, 10°/SEC | |

- LO2/LH2
- STAGED COMBUSTION CYCLE
- REGEN. FUEL COOLED
- CONTINUOUS THROTTLING 65 - 109% RPL
- LIFE: 7.5 HRS, 55 STARTS
- LEAD TIME - 48 MONTHS
- PRODUCTION COST (ROCKETDYNE)
  - $45-50M/BASIC ENGINE (QNTY 2-8/YR, 4 TOTAL)
  - $35-40M/EXPENDABLE ENGINE (QNTY 8-12/YR, 30 TOTAL)
- OPERATIONS COST (ROCKETDYNE)
  - $1.3M/LAUNCH (3 ENGINES), AVG'D OVER 25 FLTS
  - INCLUDED MAJOR OVERHAULS AFTER EVERY 10 FLTS

# 1.8 PUMPFED ENGINE TYPE/PERFORMANCE SELECTION

## Existing Engine: F-1 (uprated)

| | MPL | NPL | EPL |
|---|---|---|---|
| • SL THRUST, LB | 1.25M | 1.522M | 1.80M |
| • SL Isp, SEC | | 265.4 | 271.9 |
| • VAC Isp, SEC | | 304.1 | 306 |
| • Pc, PSIA | 806 | 982 | 1135 |
| • MR | | 2.27 | |
| • AREA RATIO | | 16 | |
| • D exit, IN | | 143.5 | |
| • LENGTH, IN | | 220.4 | |
| • WEIGHT, LB | (DRY) 19,647; (WET) 21,649 | | |
| • GIMBALLING | ±6°, 10°/SEC, 1RAD/SEC2 | | |

- LO2/RP1
- GAS GENERATOR CYCLE
- REGEN. FUEL COOLED
- CONTINUOUS THROTTLING 1.25 - 1.8MLBF
- LIFE: 5,000 SEC, 30 STARTS, 25 FLTS CAPABILITY,
  50 FLTS ACHIEVED WITH OVERHAUL
- LEAD TIME - 48 MONTHS
- NON-RECURRING COST (ROCKETDYNE)
  $85M FOR TOOLING & SUPPORT EQUIPMENT
- PRODUCTION COST (ROCKETDYNE)
  $14-16M/ENGINE (QNTY 12-16/YR, 45 TOTAL)
- OPERATIONS COST (ROCKETDYNE)
  MAJOR OVERHAUL AFTER 25 FLTS
  60% FIRST UNIT COST FOR MAJOR OVERHAUL

# 1.8 PUMPFED ENGINE TYPE/PERFORMANCE SELECTION

## New Gas Generator Cycle Engine

- PROVIDE QUALITATIVE EVALUATION FOR ALL OPTIONS
- VALIDATE ALL PERFORMANCE ENGINE DATA USED IN LRB AGAINST STME AND STBE POINT DESIGNS
- PROVIDE UPDATED DATA AS AVAILABLE
- COMPARE SELECTED CONCEPTS IN STBE VS. LRB

# 1.8 PUMPFED ENGINE TYPE/PERFORMANCE SELECTION

## New Gas Generator Cycle Engine Evaluation (Sheet 1 of 2)

| CRITERIA | LO2/LH2 | LO2/CH4 | LO2/C3H8 | LO2/RP1 |
|---|---|---|---|---|
| COOLANT | LH2 | CH4 | C3H8 | RP1 |
| TYPE OF COOLING | REGENERATIVE | REGENERATIVE | REGENERATIVE | REGENERATIVE |
| PERFORMANCE<br>Pc (psia)/Isp,v (sec) | HIGHEST<br>~3000/~440 | GOOD<br>~2800/~340 | MEDIUM<br>~2800/~330 | POOR<br>~1500/~315 |
| IGNITION CHARACTERISTICS | GOOD | MEDIUM | POOR | POOR |
| COMBUSTION STABILITY | VERY GOOD | GOOD | MEDIUM | POOR |
| ENGINE OPERATIONAL COMPLEXITY | HIGH | MEDIUM | MEDIUM | LOW |
| THROTTLEABILITY | TBD | TBD | TBD | TBD |
| REUSABILITY | HIGH | HIGH | LOW | LOW |
| CONTROL AUTHORITY | TBD | TBD | TBD | TBD |
| COST - DDT&E<br>FIRST UNIT | HIGH<br>HIGH | MEDIUM<br>MEDIUM | MEDIUM<br>MEDIUM | LOW<br>LOW |
| TECHNOLOGY RISK | LOW | MEDIUM | MEDIUM | LOW |
| SCHEDULE RISK | LOW | MEDIUM | MEDIUM | LOW |

# 1.8 PUMPFED ENGINE TYPE/PERFORMANCE SELECTION

## New Gas Generator Cycle Engine Evaluation (Sheet 2 of 2)

| CRITERIA | LO2/CH4/LH2 | LO2/C3H8/LH2 | LO2/RP1/LH2 | NTO/MMH |
|---|---|---|---|---|
| COOLANT | LH2 | LH2 | LH2 | MMH |
| TYPE OF COOLING | REGENERATIVE | REGENERATIVE | REGENERATIVE | REGENERATIVE |
| PERFORMANCE<br>Pc (psia)/Isp,v (sec) | VERY GOOD<br>~3600/~365 | VERY GOOD<br>`3600/~360 | VERY GOOD<br>~3600/~355 | POOR<br>~1500/~290 |
| IGNITION CHARACTERISTICS | VERY GOOD | GOOD | GOOD | VERY GOOD |
| COMBUSTION STABILITY | VERY GOOD | GOOD | GOOD | VERY GOOD |
| ENGINE OPERATIONAL COMPLEXITY | HIGH | HIGH | HIGH | LOW |
| THROTTLEABILITY | TBD | TBD | TBD | TBD |
| REUSABILITY (CLEAN BURN) | HIGH | HIGH | HIGH | HIGH |
| CONTROL AUTHORITY | TBD | TBD | TBD | TBD |
| COST - DDT&E<br>FIRST UNIT | HIGH<br>HIGH | HIGH<br>HIGH | HIGH<br>HIGH | LOW<br>LOW |
| TECHNOLOGY RISK | HIGH | HIGH | HIGH | LOW |
| SCHEDULE RISK | MEDIUM | HIGH | HIGH | LOW |

# 1.8 PUMPFED ENGINE TYPE/PERFORMANCE SELECTION

## New GG Engine Performance Data Used in Previous Trades/Analyses

- ENGINE DATA USED WERE ADEQUATE FOR PRELIMINARY TRADES/ANALYSES PURPOSES

| ENGINE (1) | PC (2) (PSIA) | MR | DATA SOURCE | % MEAN DISPERSION (3) | | |
|---|---|---|---|---|---|---|
| | | | | Dexit | Isp,v | WEIGHT |
| LO2/LH2 (5) | 3000 | 6.0 | P&W LCEE (GG) | -2.4 | 1.1 | -6.0 |
| LO2/CH4 | 2333 | 3.0 | P&W HC ENGINE | -4.1 | -0.6 | -10.8 |
| LO2/C3H8 | 2333 | 2.7 | P&W HC ENGINE | -2.5 | -3.5 | -8.1 |
| LO2/RP1 | 1275 | 2.7 | P&W HC ENGINE | -5.0 | -1.5 | -14.9 |
| LO2/CH4/LH2 (5) | 3067 | 3.5 | P&W HC ENGINE | -3.2 | 0.8 | -10.2 |
| LO2/C3H8/LH2 | 3067 | 3.2 | P&W HC ENGINE | -1.9 | 1.6 | -2.7 |
| LO2/RP1/LH2 | 3067 | 3.0 | P&W HC ENGINE | -2.2 | 2.6 | -5.4 |
| NTO/MMH(4) | 1000 | 2.2 | ODE w/ nc*=0.95, nn=0.95 | N/A | N/A | N/A |

(1) ASSUMED SINGLE THRUST LEVEL FOR SIZING OF ENGINE; EXPENDABLE ENGINE WEIGHT.
(2) CHAMBER PRESSURE FROM P&W'S STBE AT NPL AND LO2/LH2 LOW COST EXPENDABLE ENGINE OF ALS.
(3) STBE & STME POINT DESIGNS FROM P&W, RD AND AJ WERE USED AS REFERENCE. THEIR PC, MR & AR WERE USED IN P&W PARAMETRIC EQUATIONS TO GENERATE NEW DATA. ARITHMATIC ERROR OF THE EQUATIONS FROM THE REFERENCE WERE AVERAGED OVER THE 3 COMPANIES' DATA; NEGATIVE VALUE INDICATES EQUATION ESTIMATE IS LESS THAN REFERENCE.
(4) DUE TO LACK OF DATA, LO2/RP1 ENGINE LENGTH & WEIGHT EQUATIONS WERE USEDFOR CONSERVATIVE ESTIMATES.
(5) RECENT STME/STBE DATA, 1/88, WERE USED AS REFERENCE.

# 1.8 PUMPFED ENGINE TYPE/PERFORMANCE SELECTION

## New GG Engine - Improved Performance Data

- NEW IMPROVED ENGINE EQUATIONS FROM P&W GIVE BETTER ACCURACY

| ENGINE | PC (1) (PSIA) | MR | DATA SOURCE | % MEAN DISPERSION (2) | | |
|---|---|---|---|---|---|---|
| | | | | Dexit | Isp,v | WEIGHT |
| LO2/LH2 (4) | 3000 | 6.0 | P&W NEW EQNS(5) | -1.1 | 0.8 | -4.8 |
| LO2/CH4 | 2800 | 3.0 | P&W NEW EQNS(5) | 1.5 | -0.9 | -2.3 |
| LO2/C3H8 | 2800 | 2.7 | NOT AVAILABLE | N/A | N/A | N/A |
| LO2/RP1 | 1500 | 2.7 | P&W NEW EQNS(5) | -0.1 | -1.1 | -10.9 |
| LO2/CH4/LH2 (4) | 3600 | 3.5 | P&W NEW EQNS(5) | -1.6 | 0.1 | 2.1 |
| LO2/C3H8/LH2 | 3600 | 3.2 | NOT AVAILABLE | N/A | N/A | N/A |
| LO2/RP1/LH2 | 3600 | 3.0 | P&W NEW EQNS(5) | 0.4 | 1.1 | 4.0 |
| NTO/MMH(3) | 1500 | 2.2 | NOT AVAILABLE | N/A | N/A | N/A |

(1) CHAMBER PRESSURE AT EMERGENCY POWER LEVEL FROM STME/STBE.
(2) STBE & STME POINT DESIGNS FROM P&W, RD AND AJ WERE USED AS REFERENCE. THEIR PC, MR & AR WERE USED IN P&W PARAMETRIC EQUATIONS TO GENERATE NEW DATA. ARITHMATIC ERROR OF THE EQUATIONS FROM THE REFERENCE WERE AVERAGED OVER THE 3 COMPANIES' DATA; NEGATIVE VALUE INDICATES EQUATION ESTIMATE IS LESS THAN REFERENCE.
(3) DUE TO LACK OF DATA, LO2/RP1 ENGINE LENGTH & WEIGHT EQUATIONS WERE USED FOR CONSERVATIVE ESTIMATES.
(4) RECENT STBE & STME DATA USED AS REFERENCE (1/88)
(5) P&W NEW GAS GENERATOR ENGINE PARAMETRIC EQUATIONS PREPARED FOR ALS (12/87)

# 1.8 PUMPFED ENGINE TYPE/PERFORMANCE SELECTION

## New GG Engine Concept - STBE Evaluation

| ENGINE | OVERALL ENGINE RANKING | | | TECHNOLOGY RISK RANKING | | | |
|---|---|---|---|---|---|---|---|
| | P&W | RD | AJ | P&W (1) | RD (2) | AJ (3) | |
| LO2/CH4 | 2 | 1 | 2 | 4 | 1 | 1 | |
| LO2/C3H8 | 5 | 4 | 4 | 5 | 6 | 2 | |
| LO2/RP1 | 6 (4) | 2 (5) | 5 | 6 (6) | 5 | 1 | |
| LO2/CH4/LH2 | 1 | 3 | 1 | 1 | 2 | 1 | SELECTED |
| LO2/C3H8/LH2 | 4 | 6 | 3 | 3 | 4 | 2 | |
| LO2/RP1/LH2 | 3 | 5 | 3 | 2 | 3 | 2 | |

- BASIS FOR EVALUATION:
  - 100 MISSION LIFE WITH 25 MISSIONS BETWEEN OVERHAUL
  - ALL GAS GENERATOR CYCLE ENGINES
  - 160 SEC BURN TIME

(1) TECHNICAL RISK WAS NOT EVALUATED INDEPENDENTLY, BUT INCORPORATED IN TOTAL DDT&E COST RANKING REFLECTS DDT&E COST
(2) RANKING OF SUM OF DDT&E AND OPERATIONS COST RISKS
(3) QUALITATIVE RATING IN TERMS OF "DEVELOPMENT RISK" AND "ENABLING TECHNOLOGY"
(4) P&W ASSUMED HIGH OPERATIONS & SUPPORT COST FOR LO2/RP1
(5) RD ASSUMED LOW DDT&E AND RELIABILITY COST FOR LO2/RP1
(6) P&W ASSESSED LO2/RP1 AS HAVING LOWEST RISK FOR EXPENDABLE CONCEPT

# 1.8 PUMPFED ENGINE TYPE/PERFORMANCE SELECTION

## New GG Engine Concept - STBE vs. LRB Selection

STBE

- $LO_2/CH_4/LH_2$ WAS SELECTED AS THE BEST PROPELLANT CONCEPT
  - 100 MISSION LIFE WITH 25 MISSIONS BETWEEN OVERHAULS
  - 160 SECOND BURN TIME
  - $LO_2/CH_4$ MAY REPLACE PRESENT DESIGN CONCEPT

LRB

- $LO_2$/RP1 (& $ILO_2/LH_2$) SELECTED AS THE BETTER PROPELLANT CONCEPT
  - 25 MISSION LIFE (WATER RECOVERY)
  - 110-130 SECOND BURN TIME
  - MUST BE COMPATIBLE WITH CURRENT SYSTEM
  - MUST HAVE VERY LOW TECHNICAL AND SCHEDULE RISK

- **LRB RESULTS DIFFER FROM STBE RESULTS BECAUSE OF GROUNDRULES**

# 1.8 PUMPFED ENGINE TYPE/PERFORMANCE SELECTION

## Summary of Results

- ENGINE DATA USED IN PREVIOUS TRADES/ANALYSES WERE ADEQUATE FOR ESTIMATING BOOSTER SIZE OF VARIOUS PROPELLANT OPTIONS FOR COMPARISON.
- P&W'S NEW GAS GENERATOR CYCLE ENGINE PARAMETRIC EQUATIONS FOR ALS ARE FAIRLY ACCURATE IN THEIR PREDICTION AS COMPARED TO STBE/STME
- ENGINE COST ANALYSIS IS IN PROGRESS
- P&W'S NEW LOW COST ENGINE USING LO2/LH2 OR LO2/CH4 SEEM PROMISING FOR EXPENDABLE CONCEPT. THESE TWO CONCEPTS WILL BE STUDIED IN DETAILS UPON CONTRACTUAL AGREEMENT WITH P&W.

# UPDATE ON T.S. 1.8 PUMP FED ENGINE SELECTION

When the contract started, we used existing STBE and STME data plus parametric data available from engine contractors. We had to consider both expendable and reusable modes since T.S. 1.13 hadn't even started. This trade study summarizes our first cut choices up to February 1988.

After the midterm program review, we included in Rocketdyne's subcontract work on gas generator LOX/RP and LOX/LH2 engines sized for LRB. We also started working with Pratt and Whitney on split expander cycle engines using LOX/LH2 qand LOX/CH4. Therefore all the data including costs have changed.

Also at the midterm program review we selected expendable concepts, because the LRB mission model did not justify the substantial investment in reusability. This meant that engine costs, particularly recurring costs, became very important.

Our final pump fed engine selections as of 5/16/88 are a LOX/RP gas generator concept and a LOX/CH4 expander cycle.

LIQUID ROCKET BOOSTER
TRADE STUDY ERB
DECEMBER 8, 1987

## TRADE STUDY 1.9
## FINAL ERB

# PRESSURE FED ENGINE TYPE/PERFORMANCE SELECTION

GENERAL DYNAMICS
*Space Systems Division*

# 1.9 PRESSURE FED ENGINE TYPE/PERFORMANCE SELECTION
## Planning Sheet 1



**OBJECTIVE:**

- PROVIDE PERFORMANCE/WEIGHT RELATIONSHIPS FOR PROPELLANTS CONSIDERED IN PROPELLANT SELECTION TRADE STUDY
- SELECT THE BEST ENGINE CHARACTERISTICS AND PROVIDE PERFORMANCE/WEIGHT/COST RELATIONSHIPS FOR SELECTED PROPELLANTS (FROM INITIAL SCREENING)
- PROVIDE ENGINE EVALUATION FOR THESE SELECTED PROPELLANTS

**GROUNDRULES/ASSUMPTIONS/GUIDELINES:**

- INITIAL SCREENING WILL BE DONE BY ENGINE SUBCONTRACTORS WITH GD CONSENSUS
- FINAL EVALUATION WILL BE DONE BY GD WITH THE HELP OF SUBCONTRACTORS
- METALIZED PROPELLANT ENGINES WILL BE CONSIDERED FOR GROWTH OPTION ONLY
- INITIALLY 30% THROTTLING AND 5 DEG. GIMBALLING WILL BE ASSUMED UNTIL THESE RANGES ARE ESTABLISHED BY CONTROL AUTHORITY AND ABORT OPTIMIZATION TRADE
- NEAR TERM ENGINE EFFICIENCIES (PROVEN BY AVAILBLE TEST DATA) WILL BE ASSUMED BY ENGINE SUBCONTRACTORS

# 1.9 PRESSURE FED ENGINE TYPE/PERFORMANCE SELECTION

RESULTS: PERFORMANCE AND LENGTH DATA

SOURCES: TRW AND ROCKETDYNE

DATA FROM TRW:
- EFFICIENCIES
- ODE PLOTS FOR LOX/RP-1, LOX/$CH_4$, LOX/$C_3H_8$, NTO/MMH

DATA FROM ROCKETDYNE:
- EFFICIENCIES
- PRINTOUT, PLOTS, AND CURVE-FITTED RELATIONSHIPS FOR LOX/RP-1, LOX/$CH_4$ AND LOX/$C_3H_8$
- ENGINE LENGTH DATA

RECOMMENDATION:
- USE ROCKETDYNE RELATIONSHIPS FOR HYDROCARBONS DATA USED IN INITIAL TRADES OFF BY ABOUT 1%.
- USE TRW DATA FOR NTO/MMH WITH C* EFFICIENCY = 0.95 AND NOZZLE EFFICIENCY = 0.97

# 1.9 PRESSURE FED ENGINE TYPE/PERFORMANCE SELECTION

RESULTS: WEIGHT DATA AND RELATIONSHIPS

SOURCES: TRW AND ROCKETDYNE

DATA FROM TRW:
- COMPREHENSIVE WEIGHT MODEL AND PLOTS FOR ABLATIVE SYSTEM (NO DIFFERENCE BETWEEN PROPELLANTS)
- POINT DATA (AND WEIGHT BREAKDOWN) FOR REGENERATIVE AND ABLATIVE SYSTEMS)

DATA FROM ROCKETDYNE:
- TABULAR DATA FOR HYDROCARBON REGENERATIVE AND ABLATIVE SYSTEMS

| DESIGN POINT | ROCKETDYNE | | TRW | |
|---|---|---|---|---|
| | REGENERATIVE (LBS) | ABLATIVE (LBS) | REGENERATIVE (LBS) | ABLATIVE (LBS) |
| pc = 500 psia<br>T = 750 K<br>G = 10 | 5652 | 6664 | - | 6000 |
| pc = 400 psiz<br>T = 619 K<br>E = 6 | 4198 | 4827 | 3956 (Dry)<br>5106 (Wet) | 4753 (Dry)<br>5453 (Wet) |

RECOMMENDATION: USE ROCKETDYNE DATA AS DATA FOR BOTH ABLATIVE AND REGENERATIVE SYSTEMS IS AVAILABLE. DATA USED IN INITIAL TRADES OFF BY ABOUT 10%.

# 1.9 PRESSURE FED ENGINE TYPE/PERFORMANCE SELECTION

RESULTS: COST DATA

SOURCES: TRW & ROCKETDYNE

DATA FROM TRW:
- CER FOR ABLATIVE SYSTEM (LITVC, REFURBISHMENT)
- TABULAR DATA FOR OTHER SYSTEMS (POINT DATA)

DATA FROM ROCKETDYNE:
- PARAMETRIC DATA ON ABLATIVE AND REGENERATIVE SYSTEMS

| ITEM | REGENERATIVE | ABLATIVE | REGENERATIVE | ABLATIVE | COMMENTS |
|---|---|---|---|---|---|
| FIRST UNIT COST (400 PSIA, 750 K) | 6.36 M | 4.75M | 00.995M | 0.716M | • TRW MAY NOT BE FOR FIRST UNIT COST |
| DDTE COST | 377M | 296M | 209M | 168M | • ASKED FOR COST BREAKDOWN |
| LEARNING CURVE | 93% | 93% | 90% | 90% | • ASKED DAN EIMER TO FURTHER INVESTIGATE |
| RATE CURVE | VARIABLE | VARIABLE | 90% | 90% | |

RECOMMENDATION: USE ROCKETDYNE DATA AND USE 20% AS REFURBISHMENT COST FOR SEA RECOVERY.

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# 1.9 PRESSURE FED ENGINE TYPE/PERFORMANCE SELECTION

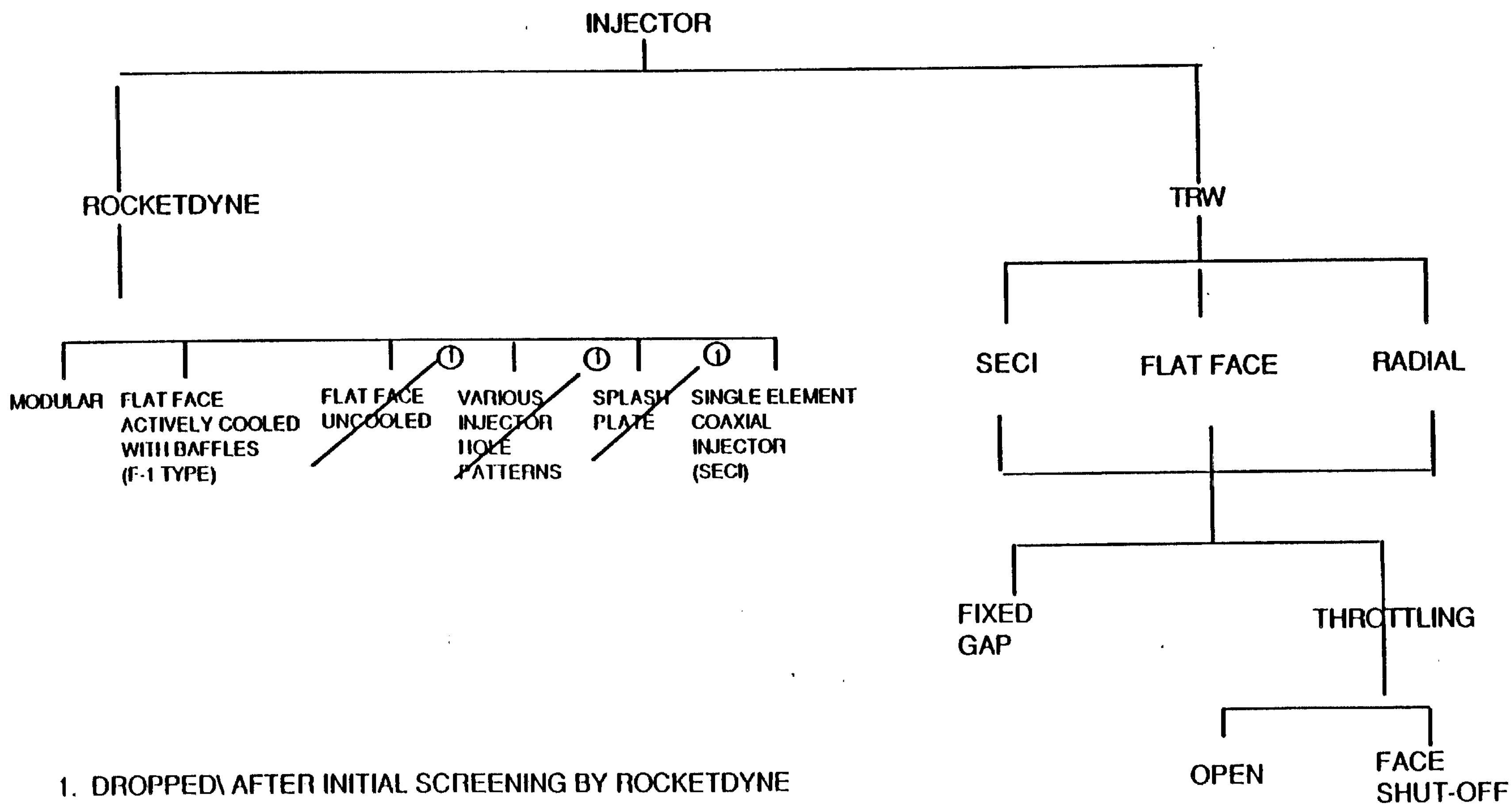
PRESSURE FED ENGINE EVALUATION

| CRITERIA | LOX/RP1 | LOX/C3M8 | LOX/CM4 | NTO/MMH |
|---|---|---|---|---|
| PERFORMANCE (ISP) | 285 SEC | 294 SEC | 308 SEC | 268 SEC |
| COMBUSTION INSTABILITY** | POTENTIAL EXISTS, BUT HAVE EXPERIENCE DEALING WITH IT | POTENTIAL EXISTS, BUT NO EXPERIENCE | LOW, BUT NO EXPERIENCE | LOW |
| COOLING PASSAGE LOSSES (REGEN) | HIGH | MEDIUM | LOW | MEDIUM |
| IGNITION COMPLEXITY | HIGH | HIGH | MEDIUM | LOW |
| INJECTOR DESIGN | MAY REQUIRE INSULATION BETWEEN LOX AND RP-1 | MINIMAL REQUIREMENT | MAY REQUIRE GASIFICATION | NO REQUIREMENT |
| REUSABILITY<br>- ABLATIVE<br>- REGENERATIVE | <br>SAME<br>LOW | <br>SAME<br>MEDIUM | <br>SAME<br>HIGH | <br>SAME<br>HIGH |
| COST | SAME (10) | SAME (10) | SAME (10) | APPROX. SAME (099) |
| TECHNOLOGY RISK | LOW BECAUSE OF PAST EXPERIENCE | MEDIUM | HIGH | LOWEST* (UNRESOLVED SAFETY, ENVIRONMENTAL & AVAILBILITY ISSUES) |
| IOC DATE | LATER | LATER | LATEST | EARLY |

**RECOMMENDATION:** LOX/RP-1 SLIGHTLY PREFERRED OVER OTHER HYDROCARBONS AS A PRESSURE FED ENGINE BECAUSE OF LOWER TECHNOLOGY RISK

# 1.9 PRESSURE FED ENGINE TYPE/PERFORMANCE SELECTION

## INJECTOR TRADE TREE




1. DROPPED\ AFTER INITIAL SCREENING BY ROCKETDYNE

# 1.9 PRESSURE FED ENGINE TYPE/PERFORMANCE SELECTION

## INJECTOR RANKING BY ROCKETDYNE

| CRITERIA | FLAT FACE | MODULAR | SECI |
|---|---|---|---|
| EFFICIENCY ( C*) | REFERENCE | 1% LESS | 2 TO 3% LESS |
| STABILITY | HIGH AFTER DEVELOPMENT | HIGH AFTER DEVELOPMENT | HIGH |
| FABRICABILITY<br>DEVELOPMENT COST<br>PRODUCTION COST | <br>HIGHEST<br>HIGHEST | <br>LOW<br>LOW | <br>MODERATE<br>LOW |
| REUSE AND REFURBISHMENT COST | HIGH | HIGH | LOW |
| THROTTLING | LOW | LOW | HIGH |

ROCKETDYNE RECOMMENDED : FLAT FACE OR MODULAR FOR REUSABLE
MODULAR FOR EXPENDABLE

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# 1.9 PRESSURE FED ENGINE TYPE/PERFORMANCE SELECTION

## INJECTOR RANKING BY TRW

| CANDIDATES | STABILITY | THROTTLING CAPABILITY | FACE SHUTOFF CAPABILITY | MANUFACTURING COST | DEVELOPMENT COST | COMBUSTION PERFORMANCE | CHAMBER SIZE | ENGINE WEIGHT | RELIABILITY | COMPATIBILITY WITH RECOVERY |
|---|---|---|---|---|---|---|---|---|---|---|
| COAXIAL (SECI) | 1 | 1 | YES | 1 | 1 | 2 | 3 | 1 | 1 | 1 |
| SHOWER HEAT (FLAT FACE) | 3 | 2 | NO | 3 | 3 | 1 | 1 | 3 | 3 | 3 |
| RADIAL | 2 | 2 | NO | 2 | 2 | 2 | 2 | 2 | 2 | 2 |

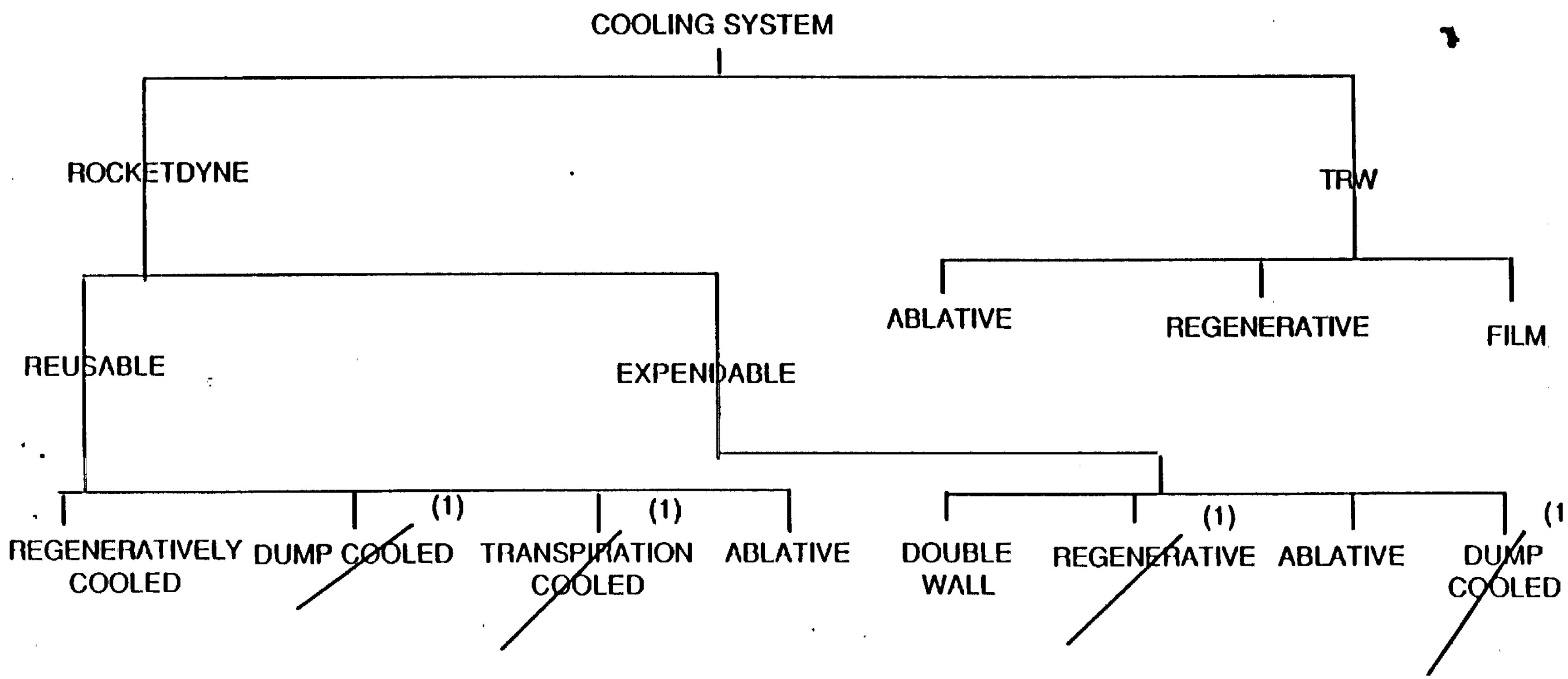
NOTE:: 1 IS THE MOST FAVORABLE RANKING, 3 IS WORST

TRW RECOMMENDED SECI WITH THROTTLING AND FACE SHUT-OFF

**RECOMMENDATION: SECI AND MODULAR BECAUSE LOWER RISK DURING DEVELOPMENT**

# 1.9 PRESSURE FED ENGINE TYPE/PERFORMANCE SELECTION

## THRUST CHAMBER/NOZZLE COOLING TRADE TREE




(1) DROPPED AFTER INITIAL SCREENING

# 1.9 PRESSURE FED ENGINE TYPE/PERFORMANCE SELECTION

## ROCKETDYNE THRUST CHAMBER/NOZZLE COOLING SELECTION

| CRITERIA | TUBE WALL CHAMBER NOZZLE REGENERATIVELY COOLED BY SINGLE PASS CIRCUIT | ABLATIVE, SILICA PHENOLIC COMBUSTION CHAMBER WITH CARBON/CARBON NOZZLE | CORRUGATIVE WALL TYPE CHAMBER |
|---|---|---|---|
| RELIABILITY | HIGH | HIGH | HIGH |
| SAFETY | HIGH | HIGH | HIGH |
| COST<br>REUSABLE<br>\ EXPENDABLE | <br>LOW<br>HIGH | <br>HIGH<br>LOW | <br>N/A<br>MEDIUM |
| ENGINE WEIGHT EFFECT | 0 | 5236 LB | 0 |
| COOLANT LOSSES EFFECT | 11426 LB. | 0 | 11426 LB. |
| TECHNICAL RISK | LOW | LOW | HIGH |

ROCKETDYNE RECOMMENDED TUBE WALL REGENERATIVELY COOLED SYSTEM FOR REUSABLE CONCEPT AND ABLATIVE COMBUSTION CHAMBER FOR EXPENDABLE CONCEPT

# 1.9 PRESSURE FED ENGINE TYPE/PERFORMANCE SELECTION

## TRW THRUST CHAMBER/NOZZLE COOLING SELECTION

| CANDIDATES | RELIABILITY | COST | WEIGHT | EFFECTIVENESS | GEOMETRICAL STABILITY | COMPABIBILITY WITH RECOVERY |
|---|---|---|---|---|---|---|
| ABLATIVE | 1 | 1 | 1 | 1 | 2 | 1 |
| REGENERATIVE | 2 | 3 | 3 | 1 | 1 | 3 |
| FILM | 2 | 2 | 2 | 1 | 1 | 2 |

TRW RECOMMENDED ABLATIVE COOLING SYSTEM

**RECOMMENDATION:** CARRY BOTH TUBE WALL REGENERATIVELY COOLED AND ABLATIVE SYSTEMS BECAUSE OF SOME SAFETY CONCERNS FOR ABLATIVE SYSTEM

# 1.9 PRESSURE FED ENGINE TYPE/PERFORMANCE SELECTION

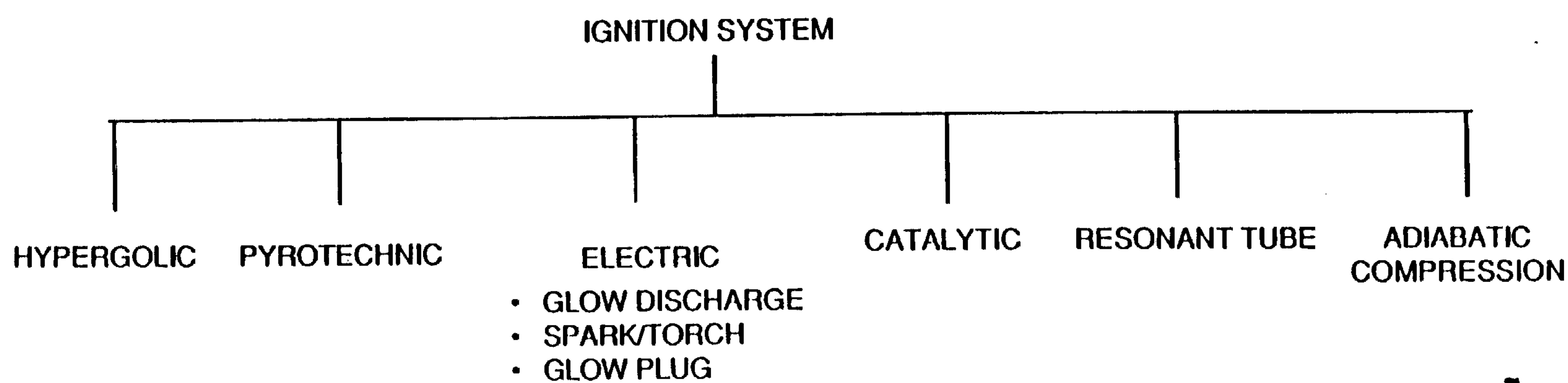
## NOZZLE SELECTION

| CRITERIA | NOZZLE TYPE | |
|---|---|---|
| | 80% BELL | 15° SEMI-ANGLE CONE |
| WEIGHT | 1186 LB | 1432 LB |
| MANUFACTURING COST | HIGH | LOW |
| PERFORMANCE | BASELINE | 0.5% LESS |

**RECOMMENDATION: 80% BELL NOZZLE**

# 1.9 PRESSURE FED ENGINE TYPE/PERFORMANCE SELECTION

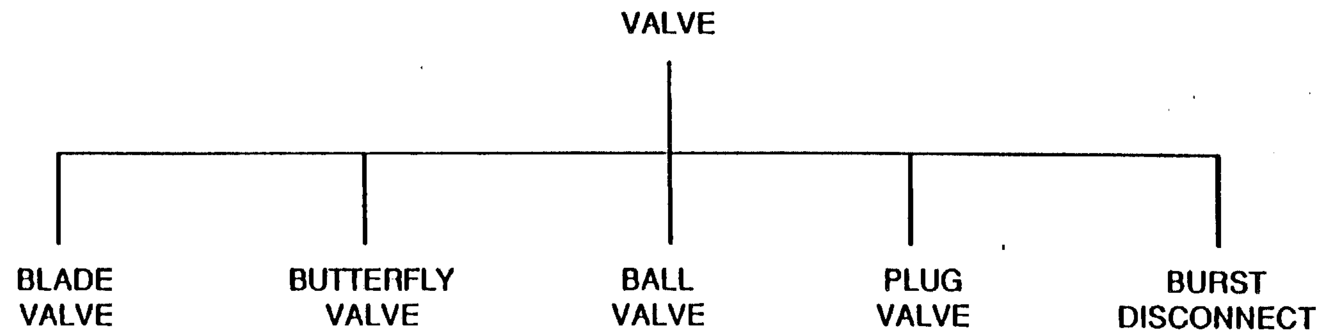
## IGNITION SYSTEM TRADE TREE/SELECTION




**RECOMMENDATION:** HYPERGOLIC SLUG BASED ON PAST EXPERIENCE AND RELIABILITY

# 1.9 PRESSURE-FED ENGINE TYPE/PERFORMANCE SELECTION

## Valve Selection Trade Tree



# 1.9 PRESSURE-FED ENGINE TYPE/PERFORMANCE SELECTION

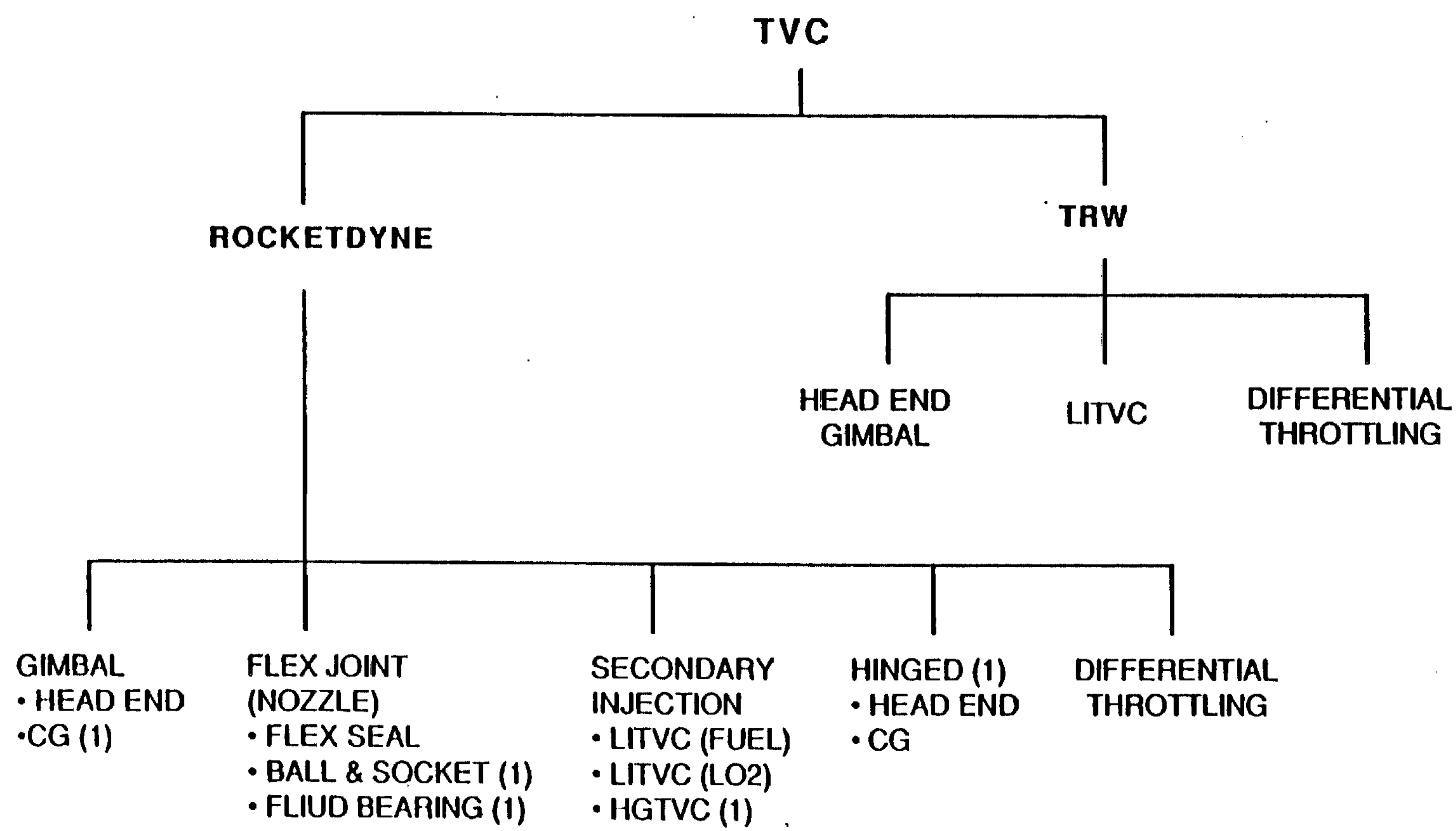
## Valve Selection

| CRITERIA | BLADE VALVE | BUTTEFLY VALVE | BALL VALVE | PLUG VALVE | BURST DISC |
|---|---|---|---|---|---|
| RELIABILITY & SAFETY | HIGH | HIGH, stays in set position | HIGH | HIGH | HIGH |
| THROTTLING<br>• ACCURACY<br>• LINEARITY | HIGH<br>MEDIUM | HIGH<br>GOOD | MED-HIGH<br>GOOD | NONE | NONE |
| RESPONSE TIME | MEDIUM | MEDIUM | MEDIUM | RAPID | RAPID |
| PRESSURE DROP<br>POWER REQ'D | ~0<br>MEDIUM | ~10 PSI<br>HIGH | ~0<br>LOW | NONE | NONE |
| WEIGHT | LOW | MEDIUM | MEDIUM | LOW | LOW |
| COST | LOW-MED | MEDIUM | MEDIUM | LOW | LOW |
| TECHNICAL RISK | LOW (some concern on acoustic vibration) | LOW | LOW (large experience) | LOW | LOW |

**RECOMMENDATION: BALL VALVE, ASSUMING VALVE THROTTLING REQUIRED**

# 1.9 PRESSURE-FED ENGINE TYPE/PERFORMANCE SELECTION

## TVC Trade Tree




(1) ELIMINATED AFTER INITIAL EVALUATION WITH ROCKETDYNE

# 1.9 PRESSURE-FED ENGINE TYPE/PERFORMANCE SELECTION

## Rocketdyne TVC Rating

| CRITERIA | LITVC | HEAD END GIMBAL | DIFFERENTIAL THROTTLING |
|---|---|---|---|
| RELIABILITY/ SIMPLICITY | Multiple valve operation with auxiliary equipment | Bellows in line; Gimbal Actuators with auxiliary equipment | Complex Control/ Guidance Software |
| WEIGHT | Heavy due to weight & volume of propellants | MEDIUM | LIGHT |
| COST | MEDIUM | HIGH | LOW |
| ENVELOPE | SMALL | LARGE | SMALL |
| EXPERIENCE/RISK | LOW RISK | LOW RISK | NO EXPERIENCE |

ROCKETDYNE PREFERS HEAD-END GIMBAL

## 1.9 PRESSURE-FED ENGINE TYPE/PERFORMANCE SELECTION

### TRW TVC Rating

| CANDIDATES | WEIGHT | COST | EFFECTIVENESS | RESPONSE | COMPATIBILITY WITH RECOVERY | COMMENTS |
|---|---|---|---|---|---|---|
| DIFFERENTIAL THROTTLING | 1 | 1 | 1 | 2 | 2 | Requires no extra hardware; just software |
| LITVC | 3 | 2 | 1 | 1 | 1 | Requires significant weight increase |
| GIMBALED ENGINE | 2 | 3 | 1 | 3 | 3 | Requires hydraulics & recovery loads impact design |

NOTE: 1 is the most favorable ranking, 3 is the worst

TRW PREFERED DIFFERENTIAL THROTTLING

RECOMMENDATION: HEAD-END GIMBAL & DIFFERENTIAL THROTTLING.
DIFFERENTIAL THROTTLING NEEDS FURTHER EVALUATION TO SEE IF IT MEETS CONTROL REQUIREMENTS.

# 1.9 PRESSURE-FED ENGINE TYPE/PERFORMANCE SELECTION

## Summary

• ENGINE CONFIGURATION SELECTION FOR LO2/RP1 (SELECTED PROPELLANT)

| TRADES | TRW | ROCKETDYNE | RECOMMEDATION |
|---|---|---|---|
| CHAMBER PRESSURE OPTIMIZATION | $L^* = 96in$<br>$MR = 2.5$<br>$CR = 2.2$<br>$L = 153$ in | $L^* = 67in$<br>$MR = 2.5$<br>$CR = 2.2$<br>$L = 156$ in | Dependent on Injector |
| THROTTLING RANGE | - | - | Initially 30% (TBD) |
| THROTTLING TYPE | Valve & Injector | Valve | TBD |
| INJECTOR | SECI | Reusable: Flat Face or Modular<br>Expendable: Modular | SECI or Modular |
| NOZZLE | 80% Bell | 80% Bell | 80% Bell |
| COOLING | Ablative | Reusable: Regenerative<br>Expendable: Ablative | Regenerative<br>& Ablative |
| IGNITION | Hypergolic | Hypergolic | Hypergolic |
| VALVES | Ball | Ball | Ball |
| TVC | Differrential Throttling | Head End Gimbal | Head End Gimbal & Differential Throttling |

# 1.9 PRESSURE-FED ENGINE TYPE/PERFORMANCE SELECTION

## Summary

- ENGINE PERFORMANCE AND WEIGHT DATA ARE AVAILABLE IN USABLE FORM FOR ALL PROPELLANTS CONSIDERED IN THE TRADE STUDY. COST DATA IS AVAILABLE FOR LO2/RP1 (SELECTED CONCEPT)

- LOX/RP1 IS THE PREFERRED ENGINE OUT OF ALL HYDROCARBON ENGINES BECAUSE OF ITS LOWER TECHNOLOGY RISK

- THROTTLING RANGE, THROTTLING TYPE, COOLING SYSTEM, INJECTOR TYPE AND TVC HAVE TO BE FURTHER DOWNSELECTED

## UPDATE ON T.S. 1.9 PRESSURE FED ENGINE TYPE

This trade study was completed in January 1988 based on preliminary data for LRB generated under subcontract by Rocketdyne and TRW. Many engine subsystem trades remained to be run or rerun: injector type, regenerative cooling vs. ablative coatings, head end gimbal vs. nozzle only. The data had to cover both expendable and reusable concepts.

After the midterm review, when expendable concepts were recommended, Rocketdyne has continued under contract. We continue to recommend LOX/RP as the propellant combination. The choice of subsystems was made difficult by lack of experience with LOX/RP ablative materials. Clearly there are a number of technology gaps which need to be demonstrated on the MSFC pressure-fed LRB test bed program.

Our current baseline features regenerative cooling, head-end gimbaling, and modular injectors.

REPORT NO. GDSS-LRB-88-024

# LIQUID ROCKET BOOSTER
# TRADE STUDY NO. 1.10
# IGNITION SEQUENCE AND HOLD DOWN
# FINAL REPORT

22 FEBRUARY, 1988

PREPARED UNDER
CONTRACT No.
NAS8-37137

Prepared by

GENERAL DYNAMICS SPACE SYSTEMS DIVISION
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San Diego, California 92138-5357

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## SUMMARY

Trade Study 1.10 provides a preliminary analysis of the LRB configured STS ignition and launch sequence, and the resulting transient response induced by the SSME thrust build-up. Five preliminary down select candidates were examined with the following guidelines and constraints used to complete this analysis:

1) Current SSME ignition sequence can be modified if necessary
2) Gross Thrust/Weight ratio at STS release $\leq$ 1.0
3) Minimum SSME power level at release $\geq$ 90%.
4) F-1 engine rise time and Saturn V ignition timing were used for LRB ignition analysis.

Two release techniques that have shown potential for improvement of the adverse transient characteristics are the release of the stack prior to the peak of transient loading, and employing a modified SSME ignition timing sequence that manipulates the STS transient to reduce maximum bending moment and twang at release. The early release technique indicates a possible reduction of hold down post loads by approximately 70% at the maximum and 10% at release. A potential savings of 7500 lbs of SSME propellants is also indicated. The modified SSME ignition sequence may reduce post loads by 50% at the maximum and 3% at release with a savings of 3900 lbs of SSME propellants.

These findings indicate that compliant boosters and modified ignition timing can be used to reduce the problems of hold down bolt load and twang associated with the ignition and release sequence, while providing some improvement in SSME propellant margins.

Potential problems with these techniques center around the balance of thrust between the SSMEs and LRBs at release. To hold to the constraints of T/W $\leq$ 1 and the 90% SSME power level requires that the stack be released with LRB engine thrust levels between 55% and 75%. Additionally, the low booster thrust level at release and the "slow" LRB engine rise time (as compared to the SRB) may summarily preclude the use of an explosive release system because of control authority problems near the pad and the health verification capability with 55% to 75% LRB power levels at release.

If these problems cannot be resolved, or if the final LRB configuration is stiffer than these techniques will allow, a damped launch release system designed to alleviate both base bending moment and transient launch loads appears to be a potential solution to the problems discussed here.

## Trade Study 1.10
## Ignition Sequence and Hold Down

### Table of Contents

# SECTION 1
# INTRODUCTION

A dynamic transient occurs when the Orbiter SSMEs are ignited and theSTS deflects in response to the offset thrust. When the stack springs back to a minimum deflection, the SRBs are ignited, holddown bolts are released, and the stack lifts off the launch pad. High bolt loads and bending moments are produced by the transient, and severe vibration or "twang" occurs when the vehicle is released from the launch pad.

## 1.1 OBJECTIVE

The objective of this trade study was to investigate engine ignition and release sequence characteristics for an STS configuration with Liquid Rocket Boosters, and identify methods and techniques that would:

1. Minimize twang at STS release
2. Verify engine health prior to STS release
3. Minimize LRB pre-release loads

## 1.2 GROUND RULES AND ASSUMPTIONS

Ground rules and assumptions are listed in Planning Sheet 1, Figure 1.1. Arrows indicate revisions made during the course of the study as STS data were acquired. Ground rules 1 & 2 are carried over from the overall scope of the LRB study. F-1 engine data and the Saturn V ignition sequence were used for analysis since they are existing, proven systems and considered representative of candidate booster engine characteristics.

LRB

LIQUID ROCKET BOOSTER STUDY

# TRADE STUDY #1.10 IGNITION SEQUENCE AND HOLD DOWN

## Planning Sheet 1

**OBJECTIVE:**

TO DETERMINE THE OPTIMUM ENGINE IGNITION AND RELEASE SEQUENCE TO:

(1) MINIMIZE TWANG AT LAUNCH
(2) VERIFY ENGINE HEALTH PRIOR TO RELEASE
→ (3) MINIMIZE LRB PRE-RELEASE LOADS

**GROUNDRULES/ASSUMPTIONS/GUIDELINES:**

1. REMAIN IN THE CONTEXT OF STS FLIGHT AND LAUNCH SYSTEMS BY MINIMIZING IMPACT TO EXISTING STS SYSTEM ELEMENTS, FACILITIES, AND PROCEDURES.
2. CONSIDER IMPACT OF BOTH PUMP-FED AND PRESSURE-FED FORMS OF LIQUID ROCKET PROPULSION.
→ 3. F-1 ENGINE RISE TIME AND SATURN V IGNITION SEQUENCE TIMING USED FOR LRB ANALYSIS.

Figure 1.1

# SECTION 2
# ANALYSIS

The trade study comprised the following key activities:

1. Establishing applicable requirements and guidelines
2. Analyzing the current STS ignition sequence
3. Defining alternate ignition and release methods
4. Determining preliminary properties of candidate LRB configurations
5. Sensitivity analysis
6. Analysis of candidate configurations
7. Evaluating alternate methods
8. Presenting conclusions and recommendations

## 2.1 REQUIREMENTS AND CONSTRAINTS

For this study, two requirements were identified based on STS safety guidelines as shown in Figure 2.1. Requirement 1 states that the STS will not be launched until all engine systems are verified healthy in an operating state. A verifiable, healthy operating state is currently defined for SSMEs, but is not available for conceptual booster engine designs. It will be shown later in this report that definition of such a state may be crucial to the final selection of a launch method. Requirement 2 provides that no backup system intended to sustain powered or controlled flight will be used for launch, and launch must occur with prime systems in operational control.

Constraints were significantly revised between the initiation and completion of the study as STS data were obtained. Explanations for each revision are provided below the applicable constraint in Planning Sheet 2, figure 2.1.

## 2.2 EVALUATION CRITERIA

Evaluation criteria are listed in the Criteria Applicability Matrix, Figure 2.2. Criteria were selected to be consistent with the overall study, and where the ignition sequence could have a significant impact to the final selection of an LRB configuration. Quantitative evaluations of safety, reliability, and performance were significant in the result of this study.

## 2.3 DESCRIPTION OF THE CURRENT STS IGNITION SEQUENCE

The current STS ignition and launch sequence is illustrated in Figure 2.3, Nominal STS Ignition Sequence. The SSMEs are started at 0.12 second intervals (T1 & T2), with each engine rising to full thrust in 1.905 seconds. Total rise time to full SSME

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# TRADE STUDY #1.10 IGNITION SEQUENCE AND HOLD DOWN

## Planning Sheet 2

**REQUIREMENTS:**

1. ALL ENGINES WILL BE VERIFIED FUNCTIONAL PRIOR TO RELEASE.
2. USE OF A BACKUP SYSTEM FOR FAIL OPS/FAIL SAFE PROTECTION PRIOR TO LAUNCH WILL RESULT IN A LAUNCH ABORT AND ORDERLY SHUT DOWN OF ALL ENGINES.

**CONSTRAINTS:**

→ ~~1. THE CURRENT ORBITER SSME START SEQUENCE WILL BE USED WITHOUT MODIFICATION.~~

ENGINE IGNITION TIMING IS A SOFTWARE DRIVEN FUNCTION THAT CAN BE EASILY MODIFIED IF NECESSARY. CURRENT STAGGER TIME OF 0.12 SEC IS A HOLDOVER FROM EARLY TESTING DAYS AND IS NOT CONSIDERED A CONSTRAINT.

→ 2. MAXIMUM T/W AT RELEASE = 1.0

FOR T/W >1.0, LONGITUDINAL VIBRATION PROBLEMS MAY RESULT.

→ 3. MINIMUM SSME %RPL AT RELEASE = 90%

SSME ENGINE HEALTH MONITORING LIMIT IS CURRENTLY SET TO 90%.

Figure 2.1

## Criteria Applicability Matrix worksheet (Rev-A)

Trade Study No. 1.10 — Page 1 of 2

| SELECTION CRITERION | SELECTION CRITERION DEFINITION | SELECTION CRITERION ELEMENTS | Applicability |
|---|---|---|---|
| SAFETY | EXTENT TO WHICH LRB CONCEPT MINIMIZES HAZARDS TO STS, LAUNCH FACILITIES, RANGE, AND PERSONNEL | • PROPELLANT TOXICITY/EXPLOSIVE HAZARD | |
| | | • ABORT FEASIBILITY & OPERATIONAL CONTINGENCY MODES | X |
| | | • FAILURE DETECTION | X |
| RELIABILITY FEATURES | DEGREE TO WHICH LRB CONCEPTS INCORPORATE RELIABILITY ENHANCEMENTS | • DESIGN MARGINS | X |
| | | • ENGINE OUT CAPABILITY | |
| | | • EXCESS PERFORMANCE | X |
| | | • DEGREE OF SYSTEM REDUNDANCY | X |
| STS COMPATIBILITY | DEGREE TO WHICH CANDIDATE LRB MINIMIZES IMPACTS TO EXISTING STS, INCLUDING ORBITER, EXTERNAL TANK, AND GROUND/LAUNCH FACILITIES | • STS INTERFACE MODIFICATIONS | X |
| | | • MAINTENANCE OF STS/SRB LAUNCH CAPABILITY | |
| | | • PROCESSING/LAUNCH FACILITY MODIFICATION REQM'TS | X |
| | | • LRB PROGRAM PHASE-IN FEASIBILITY DURING ON-GOING STS OPERATIONS | X |
| PERFORMANCE | ABILITY OF LRB CONCEPT TO MEET OR EXCEED REQUIRED PERFORMANCE CAPABILITY | • ENGINE/PROPULSION SYSTEM EFFICIENCY | |
| | | • LRB LIFT OFF WEIGHT | X |
| | | • MARGINS | X |
| NONRECURRING COST | INCLUDES ALL COSTS INCURRED DURING THE DESIGN, DEVELOPMENT, TEST, AND EVALUATION (DDT&E) PHASE. EXCLUDES PRODUCTION OF ALL FLIGHT HARDWARE. | • RESEARCH, DVLPMT, TEST & EVALUATION | X |
| | | • DEVELOPMENT COSTS TO FLIGHT VEHICLE IOC | X |
| | | • GROUND FACILITY ACTIVATION COSTS | X |
| | | • LRB TEST FLIGHTS | X |
| RECURRING COST | COST (UNDISCOUNTED) STARTING WITH COMPLETION OF FIRST LRB TEST FLIGHTS AND PROCEEDS THROUGH ITS DEFINED LIFE CYCLE. INCLUDES PRODUCTION COSTS OF REUSABLE HARDWARE, RECURRING OPERATIONS COSTS, AND COSTS FOR UNRELIABILITY. | • PRODUCTION OF FLIGHT HARDWARE | |
| | | • RECVRY, REFURB, AND RESUPPLY OF REUSABLE LRB HW | |
| | | • ALL OPS & MAINT COSTS FOR LRB FLT AND GRD SYSTEMS | X |
| | | • COSTS FOR LOSSES BASED ON UNRELIABILITY | |
| COST RISK | AREAS OF GREATEST COST RISK WILL BE IDENTIFIED BY ANALYZING THE SENSITIVITY OF COST TO KEY DESIGN AND PROGRAM PARAMETERS. | • RISKS IN SUCCESSFULLY INTEGRATING LRB INTO STS | |
| | | • RISKS ASSOCIATED WITH FACILITY MODIFICATIONS | |

Figure 2.2

**Criteria Applicability Matrix worksheet (Rev-A)** | Trade Study No. 1.10 | Page 2 of 2

| SELECTION CRITERION | SELECTION CRITERION DEFINITION | SELECTION CRITERION ELEMENTS | Applicability |
|---|---|---|---|
| SCHEDULE RISK | THE LIKELIHOOD THAT REQUIRED LRB SYSTEMS CAN BE DEVELOPED AND ACQUIRED ON SCHEDULE | • RISK FOR TECH DVLPMT AND INTEG INTO LRB ON NEED DATE | |
| | | • LONG LEAD PROCUREMENT | |
| TECHNICAL RISK | THE LIKELIHOOD THAT TECHNICAL ISSUES CAN BE RESOLVED | • ADVANCED TECHNOLOGY DEVELOPMENT | |
| | | • RISK IN MEETING PERFORMANCE REQUIREMENTS | |
| OPERATIONAL AVAILABILITY | DEGREE TO WHICH LRB CONCEPTS WILL BE OPERATIONALLY READY TO SUPPPORT STS MISSIONS | • INSENSITIVITY TO FAULTS, ENVIRONMENTS, ETC | |
| | | • SUPPORTABILITY AND MAINTAINABILITY | |
| | | • PROCESSABILITY AND PRODUCIBILITY | |
| | | • REUSABLE COMPONENT TURNAROUND TIME | |
| OPERATIONAL COMPLEXITY | DEGREE TO WHICH LRB CONCEPT REDUCES OPERATIONAL COMPLEXITY, REQUIREMENTS, OR PROCEDURES IN AN EFFORT TO STREAMLINE LRB PROCESSING | • BUILT IN TEST & CHECKOUT | X |
| | | • AI /EXPERT SYSTEMS FOR LAUNCH PROCESSING | X |
| | | • MISSION CONTROL SYSTEM | X |
| | | • MINIMIZES HARZARDOUS OPERATIONS | X |
| | | • ACCESSIBLE COMPONENTS | |
| ENVIRONMENTAL ACCEPTABILITY | EXTENT TO WHICH LRB CONCEPTS AVOID INTRODUCTION OF ENVIRONMENTAL POLLUTANTS OR OTHER DETRIMENTAL ENVIRONMENTAL IMPACTS. EXTENT TO WHICH LAUNCH DEBRIS IS MINIMIZED | • NON-CORROSIVE, NON-TOXIC PROPELLANTS | |
| | | • MINIMIZES RE-ENTRY DEBRIS | |
| | | • MINIMIZES AIR, WATER, AND NOISE POLLUTION | |
| GROWTH POTENTIAL | ABILITY OF THE CANDIATE LRB CONCEPT TO ACCOMMODATE INCREASES IN STS LAUNCH REQUIREMENTS<br>ABILITY OF LRB CONCEPT TO EVOLVE TO SATISFY BOOSTER REQUIREMENTS OF FUTURE LAUNCH VEHICLE SYSTEMS | • PERFORMS INCREASED STS PAYLOAD/FLT RATE REQM'TS | |
| | | • GROWTH COMPATIBILITY FOR SDV, ALS, OR SHUTTLE II | |
| | | • LEVEL OF LRB GROWTH POTENTIAL | |
| **Additional Criteria** | **Additional Criteria Definition** | | |
| | | | |

Figure 2.2 (contin.)

power is 1.905 + .12 + .12 = 2.145 seconds. The current STS configuration (with SRBs) has a bending frequency of .30 Hz, with a half wave length of 1.667 seconds. The major elements of the ignition sequence are discussed in the following sections.

### 2.3.1 SSME IGNITION

Ignition and thrust buildup of the SSMEs bends the stack forward in the X-Z plane. During the delay until release at 4.382 sec., the SSMEs burn at full power for a total of 7.07 engine seconds as follows:

| | | |
|---|---|---|
| Engine #1 | 4.382 - 1.905 | = 2.477 |
| Engine #2 | 4.382 - 1.905 - .12 | = 2.357 |
| Engine #3 | 4.382 - 1.905 - .24 | = 2.237 |
| | | 7.071 total engine sec |

SSME ignition, rise time to 100% of rated power level (RPL), and the stagger time constants T1 and T2 are detailed as item 1 in figure 2.3.

### 2.3.2 MAXIMUM RESPONSE TO OFFSET SSME THRUST

Coupled to SSME ignition, the STS stack flexes through one cycle of response, with the maximum deflection of the stack (item 2, Fig. 2.3) occuring 2.75 sec. after SSME ignition. At this point, the boosters experience the maximum base bending moment of approximately 570 million in-lbs. SRB mass is thrown in front of the bending axis, aiding the transient, but the Orbiter/ET mass opposes the transient at all times with its mass offset 43 inches behind the bending axis.

### 2.3.3 HOLD DOWN BOLT RELEASE POINT

At 6.6 seconds after first SSME ignition, the stack has sprung back to a minimum deflection point where the base bending moment is approximately 145 million in-lbs (item 3, Fig. 2.3). At this minimum moment point the SRBs are simultaneously ignited, and the 8 hold down bolts are released. This rapid booster release in the presence of a significant bending moment provides the "twang" as strain energy in the boosters rapidly dissipates as free-free vibration. A reduction in the base bending moment experienced at release will result in a reduction of the resultant twang.

### 2.3.4 SRB IGNITION

At the instant of release, the SRBs are simultaneously ignited ( Item 4, Fig. 2.3) and thrust build up occurs rapidly, reaching full power 0.35 seconds later. Approximately 0.2 sec after ignition, SRB thrust levels are sufficient to produce a total thrust to weight

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# NOMINAL STS IGNITION SEQUENCE

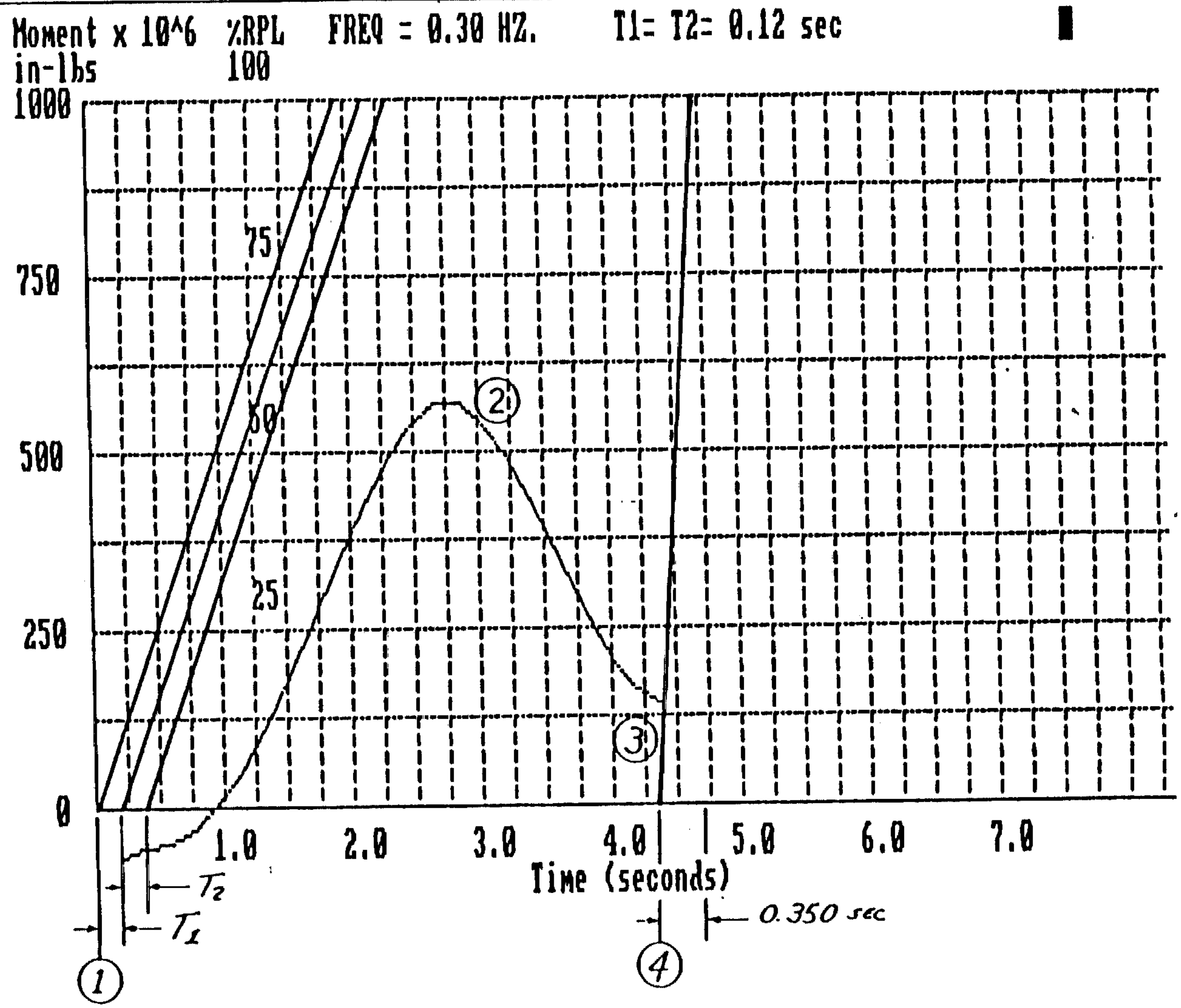


Figure 2.3

ratio (T/W) of one. The stack begins to fly off the pad with the SRBs still gaining thrust for another 0.15 sec.

## 2.4 COMPARISON OF ENGINE RISE TIMES

Rise times from 0 to 100% of RPL for the SSME, SRB, and F-1 engines are illustrated in Figure 2.4. As shown, the SRB rise time of 0.35 sec is an order of magnitude less than either the SSME (at 1.905 sec) or the F-1 (at 2.6 sec). This rapid rise time allows the current practice of releasing the stack with a T/W significantly less than one. In the 0.35 sec between STS release and achieving full SRB thrust, the stack does not rotate or translate significantly, and the vehicle flys off the pad before the dynamic state of the free stack exceeds control recovery boundaries.

With liquid propellant engines, the rise time is slow enough that a similar release sequence could result in a collision between the vehicle and fixed launch pad structures. The time between release and T/W = 1 is sufficient to allow the vehicle to move beyond recoverable control boundaries. Because of this and the requirement for health verification, LRBs must be ignited and restrained until sufficient thrust has built up. Whether or not the vehicle can safely clear the launch structure in the one to two seconds between release (at T/W= 1) and full thrust is beyond the scope of this trade, and will be addressed in future analysis. For the purpose of this study, a T/W ratio of one is assumed to be adequate.

## 2.5 DESCRIPTION OF ALTERNATIVE APPROACHES

The alternate methods of ignition and release examined in this study are summarized in Planning Sheet 4, Figure 2.5. Simultaneous ignition of SSME and booster engines was ruled out because of the difference in engine rise times and thrust. At the point where T/W = 1, the LRB engines would be at approximately 79% of RPL and the SSMEs at 48% of RPL, which violates constraint #3 for minimum SSME power at launch.

Ignition of LRB engines before SSME engines was also ruled out. Since the dynamic transient is produced by SSME thrust input, the LRB engines would be burning fuel unnecessarily while waiting for the minimum moment point in the transient response. In this situation, the consumption of LRB propellants on the launch pad reduces payload lift performance by almost 1100 lbs/sec of delay.

Thus , the current practice of igniting the SSMEs first appears to be the most efficient method. However, it will be shown that the current stagger time of 0.12 sec may not be optimal. Analysis indicates a modified SSME ignition sequence would be advantageous for controlling the dynamic transient.

For LRB engine ignition, a sequence similar to that used for the Saturn V was adopted. The five F-1 engines on the Saturn were ignited in the following order:

1. Center engine ignited
2. 0.20 second delay
3. #2 and #4 engines ignited

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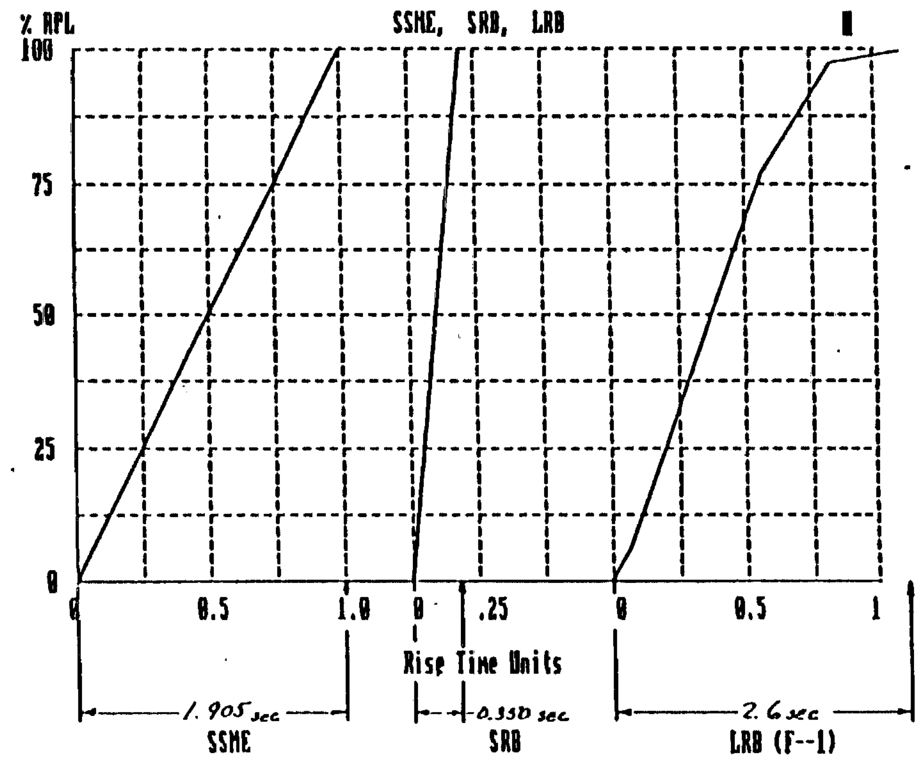
# COMPARISON OF ENGINE RISE TIMES




- SSME RISE TIME SHOWN FOR COMPARISON TO SRB & LRB
- LRB RISE TIME IS AN ORDER OF MAGNITUDE GREATER THAN SRB
  - HEALTH VERIFICATION AT LEVELS REQUIRED FOR RELEASE ARE SIGNIFICANTLY LOW (50%-70%)
  - TRANSITION TIME FROM RELEASE TO CONTROLLED FLIGHT INCREASES WITH LRB

Figure 2.4

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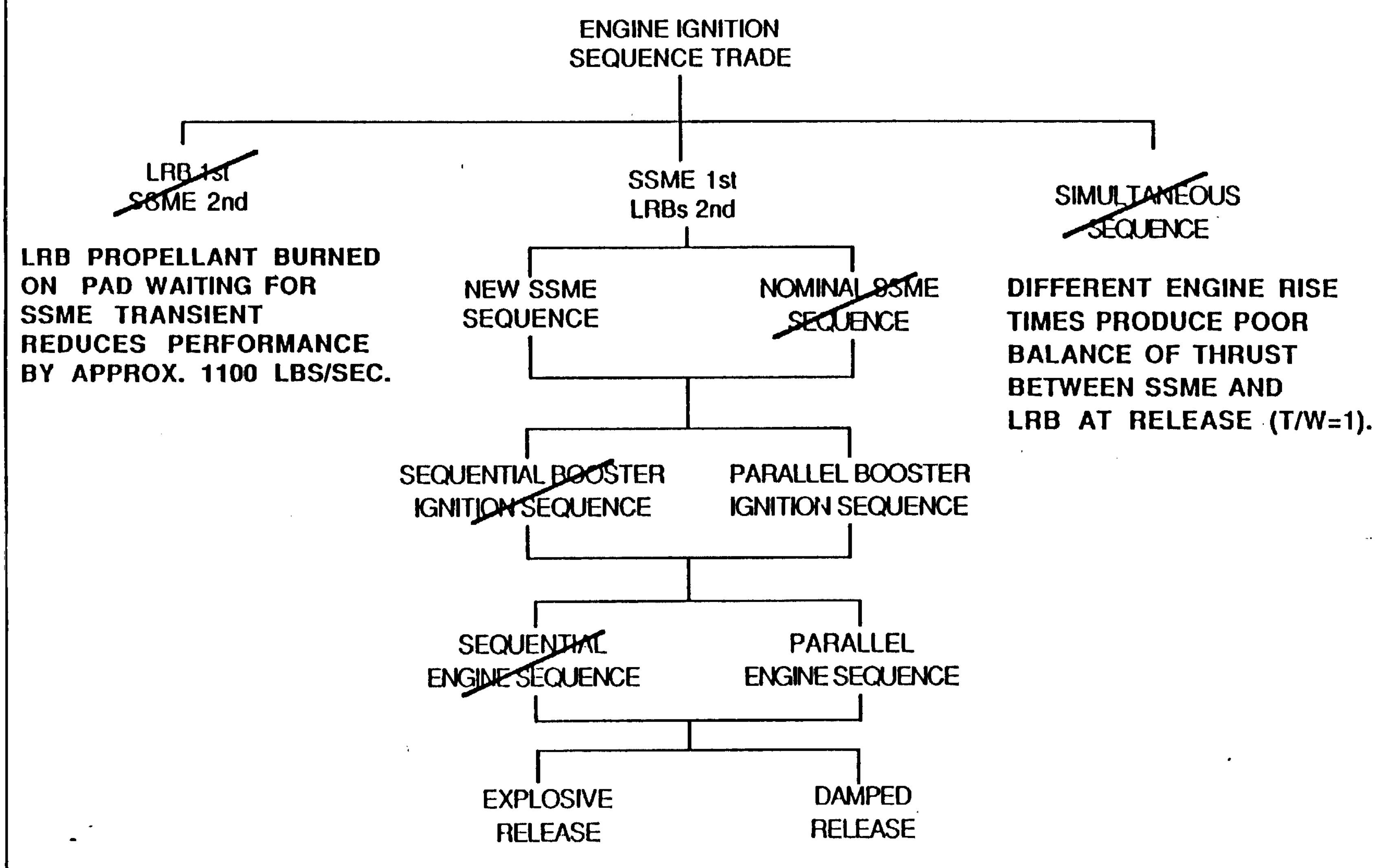
GENERAL DYNAMICS
*Space Systems Division*

# IGNITION SEQUENCE & HOLD DOWN TRADE TREE




ure 2.5

(Saturn V Ignition Sequence continued)

4. 0.20 second delay
5. #3 and #5 engines ignited

All candidate LRB configurations possess four engines, and the assumed ignition sequence is identical to steps 3 through 5 for the Saturn.

Initially, ignition overpressure was perceived to be a problem for LRBs, similar to that experienced with SRBs. However, ignition overpressure is proportional to combustion chamber pressure rise rate, which for liquid engines is an order of magnitude less than for solids. Because of this, it was assumed that simultaneous ignitition of engines on both boosters would not exceed current SRB overpressure limits. Thus the basic ignition sequence for the LRB configured STS became:

1. Simultaneously ignite 2 engines on the left booster and 2 engines on on the right booster
2. 0.20 second delay
3. Simultaneously ignite remaining 2 engines on each booster

## 2.6 RESULTS

### 2.6.1 PRELIMIANRY PROPERTIES OF LRB CANDIDATES

Preliminary design properties for the five downselected LRB configurations are listed in the first table of Figure 2.6. Booster wall thickness values were chosen to support launch loads only as opposed to thickness values to achieve stiffness comparable to SRB values.

Calculated values in the second and third tables of Figure 2.6 were used to determine bending frequencies of the STS model with each of the LRB configurations. The data represents a single degree of freedom analysis in the cantilever mode with a uniformly distributed mass cantilever beam for the boosters, and an end-loaded cantilever with a "mass-less" spring for the Orbiter/ET. A first mode frequency range of 0.15 Hz. to 0.22 Hz. was determined for the five booster configurations, and these boundary values were used for anlysis.

### 2.6.2 SENSITIVITY ANALYSIS

The dynamic response sensitivity to frequency is illustrated in Figure 2.7. The SRB configuration (.30 Hz.) is to the left, followed by LRB configuration #1B (.22 Hz.), and configuration #5D (.15 Hz.) on the right. For the three transient plots, SSME stagger is held constant at 0.12 sec.

Comparison of the three plots shows that booster bending stiffness determines the frequency of the configuration. If stiffness is decreased, the maximum bending moment and the time delay to the minimum moment both increase. This relationship

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# PRELIMINARY STIFFNESS PROPERTIES

| CONFIG # | DIA-In. | t*-In. | I-in$^4$ | EI-lb-in$^2$ | W-lbs wet | L-in |
|---|---|---|---|---|---|---|
| 1B LOX/RP-1 | 170.4 | 1.0 | $1.909\ (10)^6$ | $2.157\ (10)^{13}$ | 1,288,000 | 2100 |
| 5A LOX/LH2 | 183.6 | 0.405 | $9.778\ (10)^5$ | $1.105\ (10)^{13}$ | 661,000 | 2256 |
| 5D O2/RP-1 | 158.4 | 0.451 | $6.979\ (10)^5$ | $7.886\ (10)^{12}$ | 1,138,000 | 1956 |
| 5J LOX/LH2 | 183.6 | 0.405 | $9.778\ (10)^5$ | $1.105\ (10)^{13}$ | 657,000 | 2316 |
| 5K O2/RP-1 | 168.0 | 0.431 | $7.964\ (10)^5$ | $8.999\ (10)^{12}$ | 1,259,000 | 2064 |

* SIZED TO SUPPORT LAUNCH LOADS ONLY, MATERIAL IS AL/LI

| CONFIG # | K-lbs/in | Kf | EI equiv | m-lbs$^2$/in$^2$ | M-lbs$^2$/in$^2$ |
|---|---|---|---|---|---|
| 1B LOX/RP-1 | 40,300 | .79 | $1.702\ (10)^{13}$ | 3.2 | 6900 |
| 5A LOX/LH2 | 20,700 | .88 | $9.724\ (10)^{12}$ | 1.5 | 6200 |
| 5D O2/RP-1 | 14,700 | .91 | $7.184\ (10)^{12}$ | 3.0 | 6400 |
| 5J LOX/LH2 | 20,700 | .88 | $9.724\ (10)^{12}$ | 1.5 | 6200 |
| 5K O2/RP-1 | 16,800 | .90 | $8.097\ (10)^{12}$ | 3.2 | 6800 |

| CONFIG # | $\omega_1$ rad/sec | $\omega_2$ rad/sec | $f_{comb.}$ (hz) | |
|---|---|---|---|---|
| 1B LOX/RP-1 | 3.75 | 1.5 | .22 | ← MAXIMUM |
| 5A LOX/LH2 | 4.10 | 1.2 | .18 | |
| 5D O2/RP-1 | 2.50 | 1.0 | .15 | ← MINIMUM |
| 5J LOX/LH2 | 4.16 | 1.2 | .18 | |
| 5K O2/RP-1 | 2.59 | 1.1 | .21 | |

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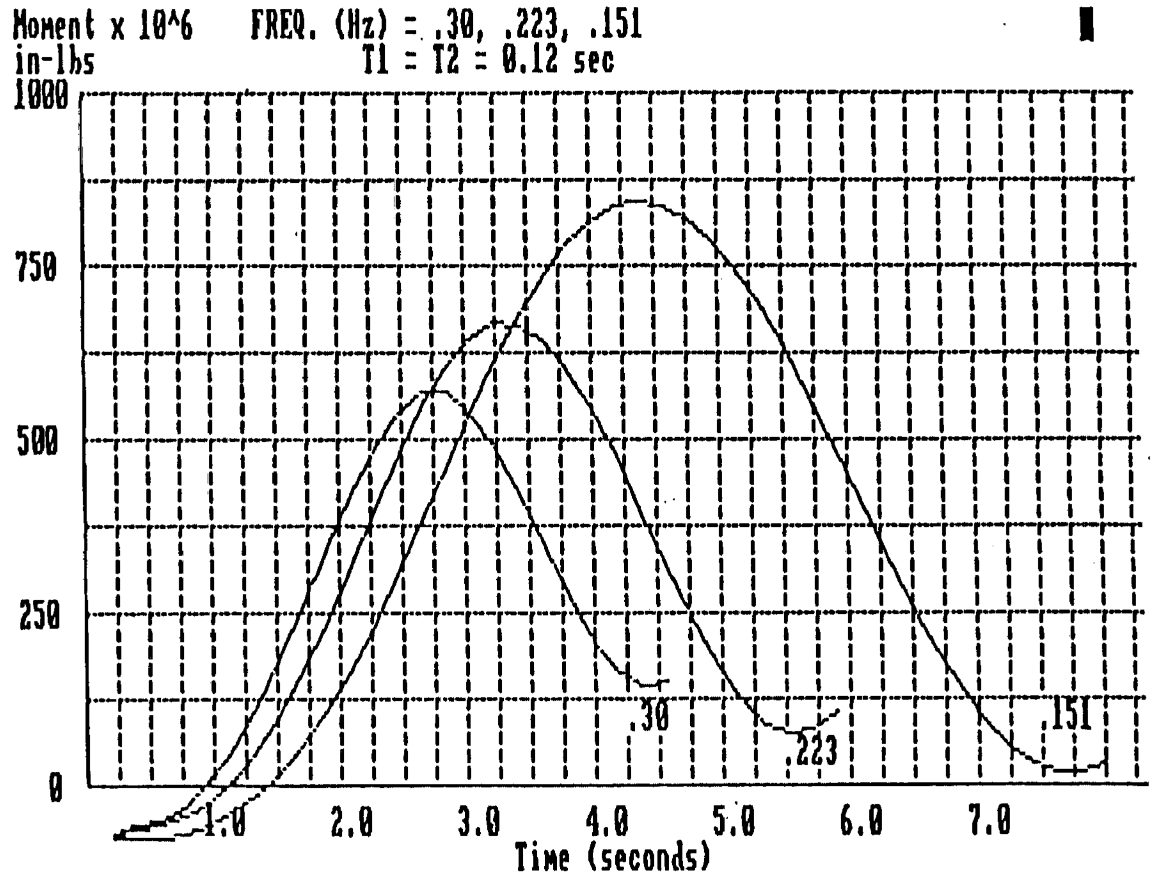
# STS DYNAMIC RESPONSE SENSITIVITY TO f




- **AS f DECREASES:**
  - MAXIMUM MOMENT (BOLT LOAD) INCREASES (DECREASED STIFFNESS)
  - TIME TO MINIMUM MOMENT INCREASES ( INCREASED DISTANCE TRAVEL)
  - MINIMUM MOMENT (TWANG EFFECT) DECREASES (LESS OVERSHOOT)

Figure 2.7

is aggravated when the half wave-length of the system is in close proximity to the total SSME rise time, i. e. :

$$(1.905 + T1 + T2) = 1/(2f) \qquad (1)$$

Fortunately, the two variables most responsible for the dynamic transient, i. e. booster stiffness, and total SSME rise time, can be varied to modify the dynamic flexure of the system.

### 2.6.3 ANALYSIS OF CANDIDATE CONFIGURATIONS

Transient response and release analyses for the .15 Hz. and .22 Hz. configurations were performed using both the nominal SSME stagger timing (T1 = T2 = 0.12 sec), and also with a series of modified values for T1. For analyses with the nominal SSME stagger timing, release of the stack was performed at the same bending moment magnitude experienced by the nominal SRB configuration. Delaying release until the minimum moment point would impose a serious impact on ET propellant margins, because of the increased time delay associated with the more compliant boosters. Two points in the transient response meet this minimum moment criteria. One occurs prior to the maximum peak and one after, both of which were examined for feasiblity.

For analysis with the modified values for T1, release of the stack was performed at the the earliest point where all SSME engines were above the minimum thrust level of 90%, and the base bending moment was less than or equal to that experienced by the SRB configuration.

For all cases, the start of the LRB ignition sequence was timed such that T/W =1 at the identified time of release.

2.6.3.1Configurations Using Nominal SSME Stagger Timing Release analysis for configuration #1B (.22 Hz.) with nominal SSME stagger is summarized in Figure 2.8 and illustrated in Figure 2.9. Release prior to the maximum bending moment cannot be accomplished because all three SSMEs have not developed thrust levels greater than 90% at the time the moment begins to exceed the defined release value. The earliest possible release time after the transient peak occurs at 5.035 sec after SSME ignition. To achieve T/W =1 at release, 4 LRB engines (ignited at 3.987 sec ) are at 73% of RPL, and the remaining 4 (ignited 0.20 sec later) are at 58.6% of RPL.

Release analysis for configuration #5D (.15 Hz.) with nominal SSME stagger is summarized in Figure 2.10 and illustrated in Figure 2.11. For this more compliant booster, release prior to the maximum moment is feasible. Here, the response to SSME ignition is delayed enough that all SSMEs are above 90% of RPL at the time the moment increases beyond the defined release value. Release at the defined moment magnitude occurs prior to the peak at 2.039 sec with 4 LRBs at 73.1% and 4 at 58.7% of RPL. While not shown in Figure 2.11, by "backing down" the transient plot to the point where the last ignited SSME is at 90% of RPL(consistent with constraint

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# RELEASE ANALYSIS: CONFIGURATION #1B

## GROUNDRULES:

- T/W = 1.0 AT RELEASE
- MINIMUM SSME RPL = 90% AT RELEASE
- BENDING MOMENT AT RELEASE = 144.9 M in-lbs (CURRENT PRACTICE)
- GLOW = 4,404,468 lb.
- $T_{LRB}$ = 619,482 lb.
- $f$ = 0.223 HZ.

## RELEASE ANALYSIS:

For Release At Time Of Minimum Bending Moment : $T_1$ = 0.867 RTU (1.652 sec)

$T_2$ = 2.643 RTU (5.035 sec)

$T_{SSME}$ @ $T_1$ : ~~1 @ 86.7%~~
~~1 @ 80.4%~~
~~1 @ 74.1%~~

$\boxed{\text{SSME RPL < 90\%}}$

$T_{SSME}$ @ $T_2$ : 3 @ 100%

$T_{SSME}$ = 3(381,000)= 1,143,000 lb

$T_{LRB}$ ((4(%RPL) + 4(%RPL-.144)) = GLOW - $T_{SSME}$

## LRB THRUST LEVELS:

@ $T_1$ : VIOLATES GROUNDRULE FOR MINIMUM % RPL

@ $T_2$ : 4 LRBE @ 73.0% RPL
4 LRBE @ 58.6% RPL

Figure 2.8



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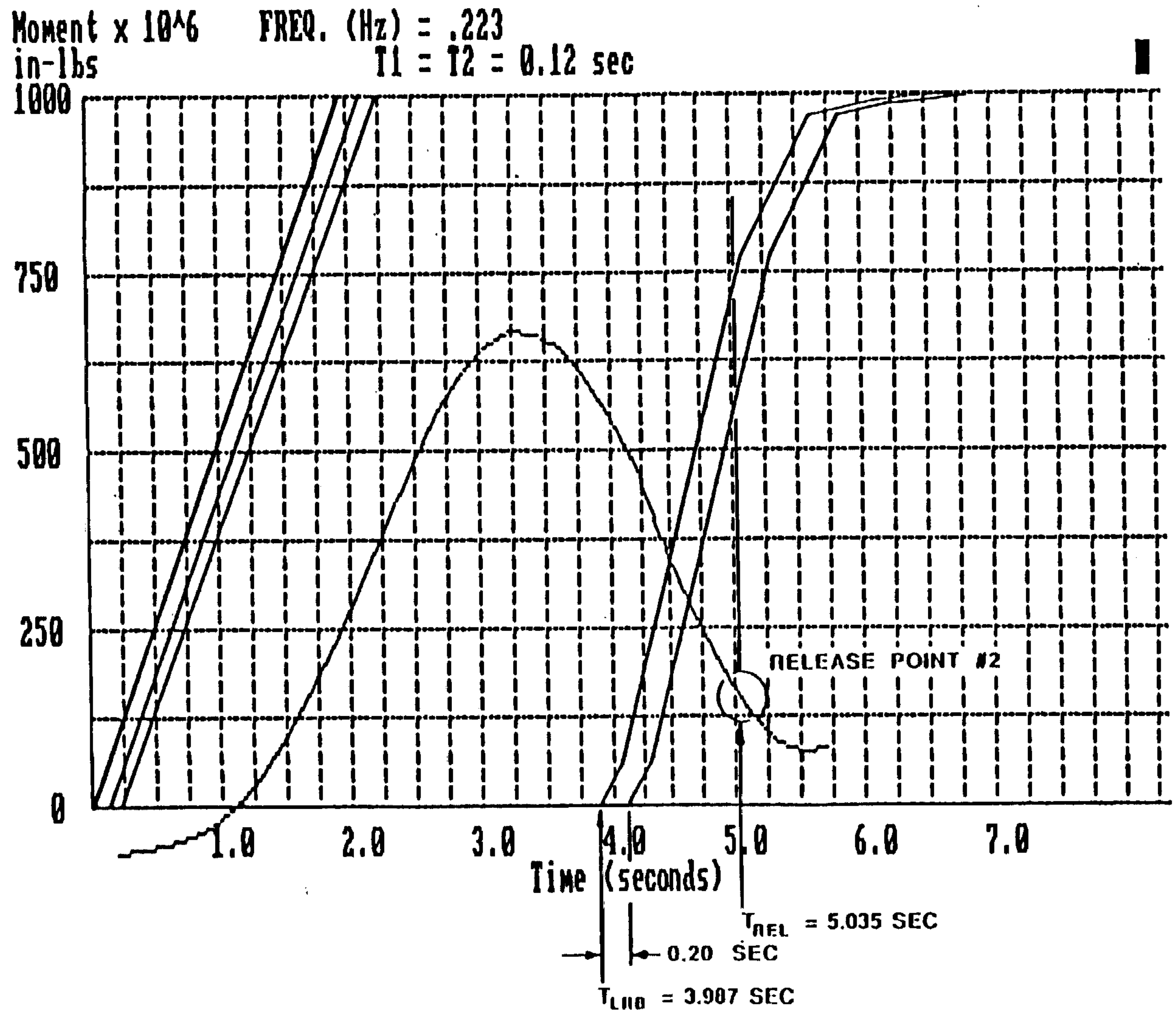
# RELEASE ANALYSIS: CONFIGURATION #1B




Fi' 're 2.9

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# RELEASE ANALYSIS: CONFIGURATION #5D

## GROUNDRULES:

- T/W = 1.0 AT RELEASE
- MINIMUM SSME RPL = 90% AT RELEASE
- BENDING MOMENT AT RELEASE = 144.9 M in-lbs (CURRENT PRACTICE)
- GLOW = 4,128,707 lb.
- $T_{LRB}$ = 568,926 lb.
- f = 0.151 HZ.

## RELEASE ANALYSIS:

For Release At Time Of Minimum Bending Moment: $T_1$ = 1.070 RTU (2.039 sec)

$T_2$ = 3.60 RTU (6.858 sec)

$T_{SSME}$ @ $T_1$ : 1 @ 100%
1 @ 100%
1 @ 96.8%
$T_{SSME}$ = 2.968(381,000)= 1,130,808 lb

$T_{SSME}$ @ $T_2$ : 3 @ 100%
$T_{SSME}$ = 3(381,000)= 1,143,000 lb

$$T_{LRB}\ ((4(\%RPL) + 4(\%RPL-.144)) = GLOW - T_{SSME}$$

## LRB THRUST LEVELS:

@ $T_1$ : 4 LRBE @ 73.1% RPL
4 LRBE @ 58.7% RPL

@ $T_2$ : 4 LRBE @ 72.8% RPL
4 LRBE @ 54.4% RPL

Figure 2.10

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# RELEASE ANALYSIS: CONFIGURATION #5D

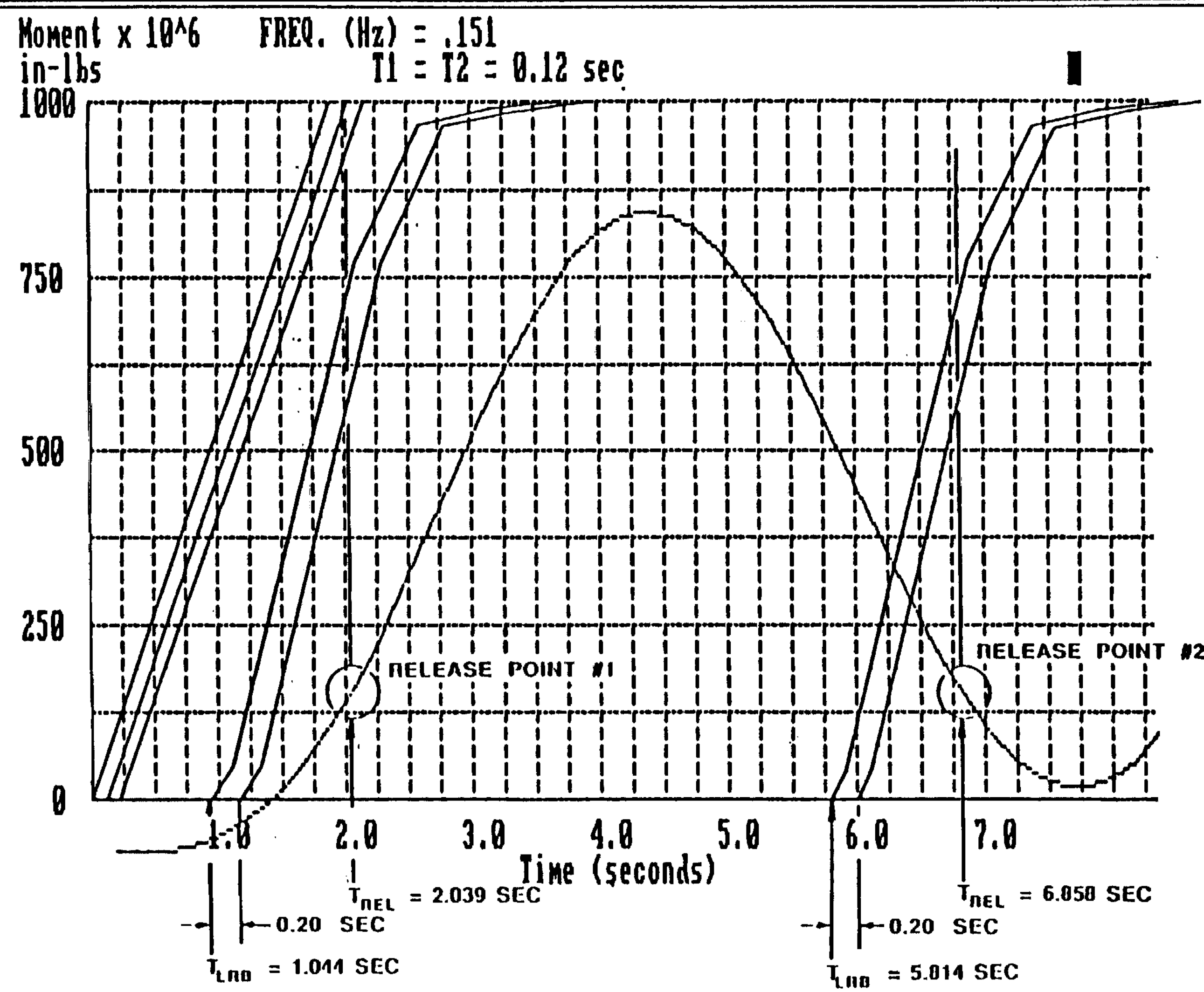


Fig. 2.11

#3) additional improvements in ET propellant margins, bending moment at release, and the time delay to release can be realized. The earliest possible release time after the transient peak occurs at 6.858 sec after SSME ignition. To achieve T/W =1 at release, 4 LRB engines (ignited at 5.814 sec ) are at 72.8% of RPL, and the remaining 4 (ignited 0.20 sec later) are at 54.4% of RPL.

The increase in maximum moment, deflections, and time delay encountered with LRBs using "nominal" SSME ignition stagger timing indicates these configurations should not proceed through a full cycle of response prior to release. Consequently, analyses were performed on the two LRB configurations to determine the potential benefit of modifying the total SSME rise time.

2.6.3.2 Modified SSME Rise Time Modification consisted of varying the stagger time between the first and second engine starts (T1), to negate the relationship between total rise time and the half wave-length of the system (Section 2.6.2). Stagger time between second and third engine starts (T2) was held at 0.12 sec. Discussion of the following figures is in comparison to Figure 2.3, Nominal STS ignition Sequence.

A series of transient response plots for configturation #1B (.22 Hz.) with T1 values of 3.0, 3.5, 4.0, 4.5, and 5.0 seconds is illustrated in Figure 2.12. For all cases plotted, a significant decrease in the maximum bending moment is shown, and for cases with $3.5 \leq T1 \leq 4.0$ sec., release can be accomplished to satisfy the constraints for bending moment release limit and the minimum SSME power level constraint of 90%.

At first glance, the time delay until possible release appears to be significantly greater than for the current SRB configuration. However, the dashed line labeled "EQUIVALENT NOMINAL SSME ENGINE SECONDS" denotes the boundary where the same amount of ET propellants (as the SRB configuration) would be consumed. Comparison of this boundary with the boundary for release points labeled "SSME POWER LEVELS @ 100, 96.3, & 90 %" demonstrates that a substantial increase in ET propellant margins is possible.

Similar plots for configuration #5D are shown in Figure 2.13, with values for T1 of 4.0, 4.5, 5.0, and 5.5 seconds. For all cases, a significant decrease in the maximum bending moment is demonstrated, and for the cases where $T1 \geq 5.0$, a substantial decrease in the bending moment at release is realized. Additionally the ET propellant margins gained by release at minimum SSME thrust levels are even greater than that for the .22 Hz. case.

## 2.7 ALTERNATIVE EVALUATION

A summary of release data for the analyzed configurations is compared to appropriate selection criteria in Figure 2.14. Configurations #1B and #5D RELEASE #2 require addlitional consumption of ET propellants (2033 lbs and 7688 lbs respectivley) prior to launch. Reduction of ET propellants from the nominal margins poses a significant impact to Orbiter intact abort and cross range capability. Because of the impact to safety, both of these release techniques are immediately eliminated from further evaluation.

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LIQUID ROCKET BOOSTER STUDY

# DYNAMIC RESPONSE W/MODIFIED T1: f = .223

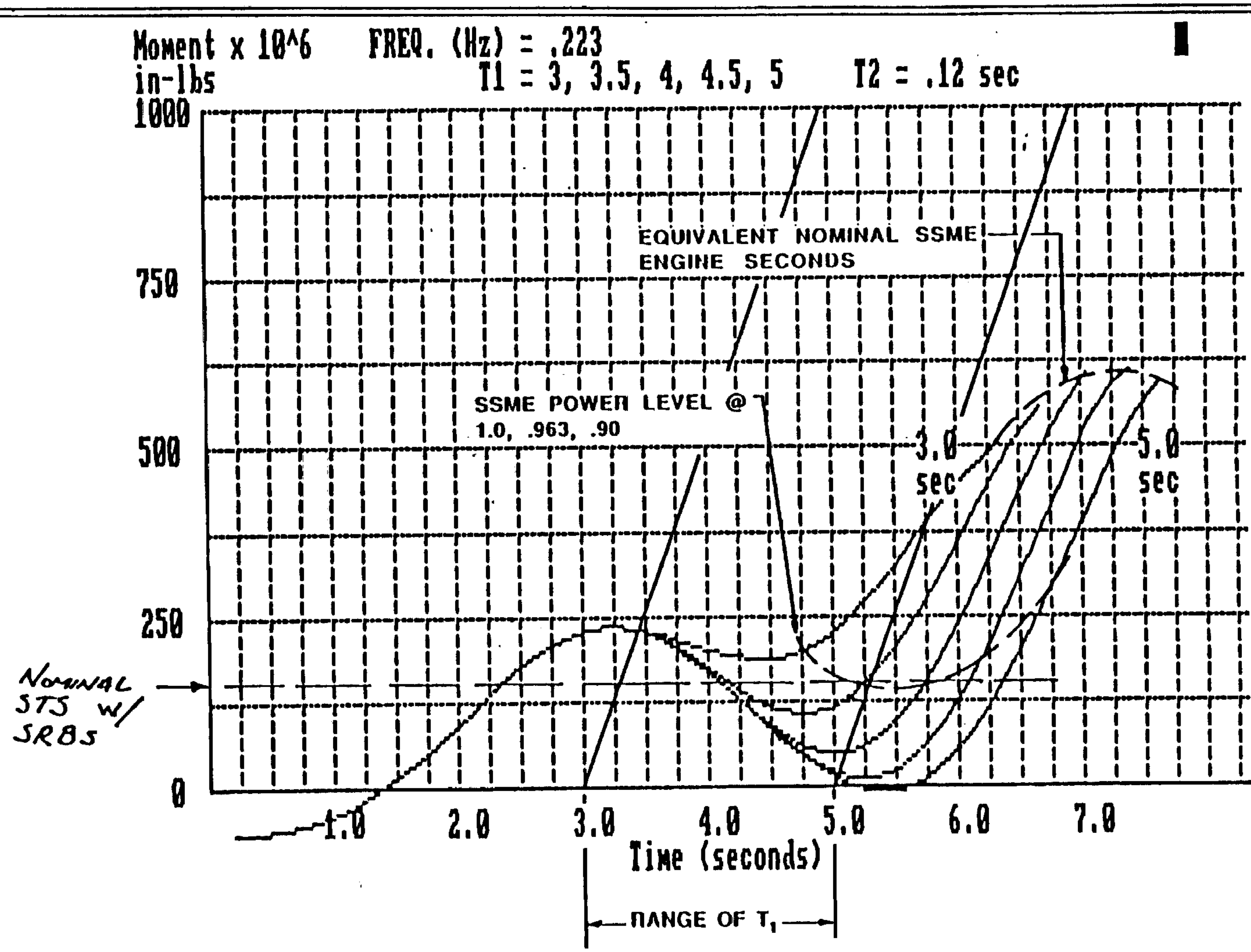


Figure 2.12

LRB
LIQUID ROCKET BOOSTER STUDY

# DYNAMIC RESPONSE W/MODIFIED T1: f = .151

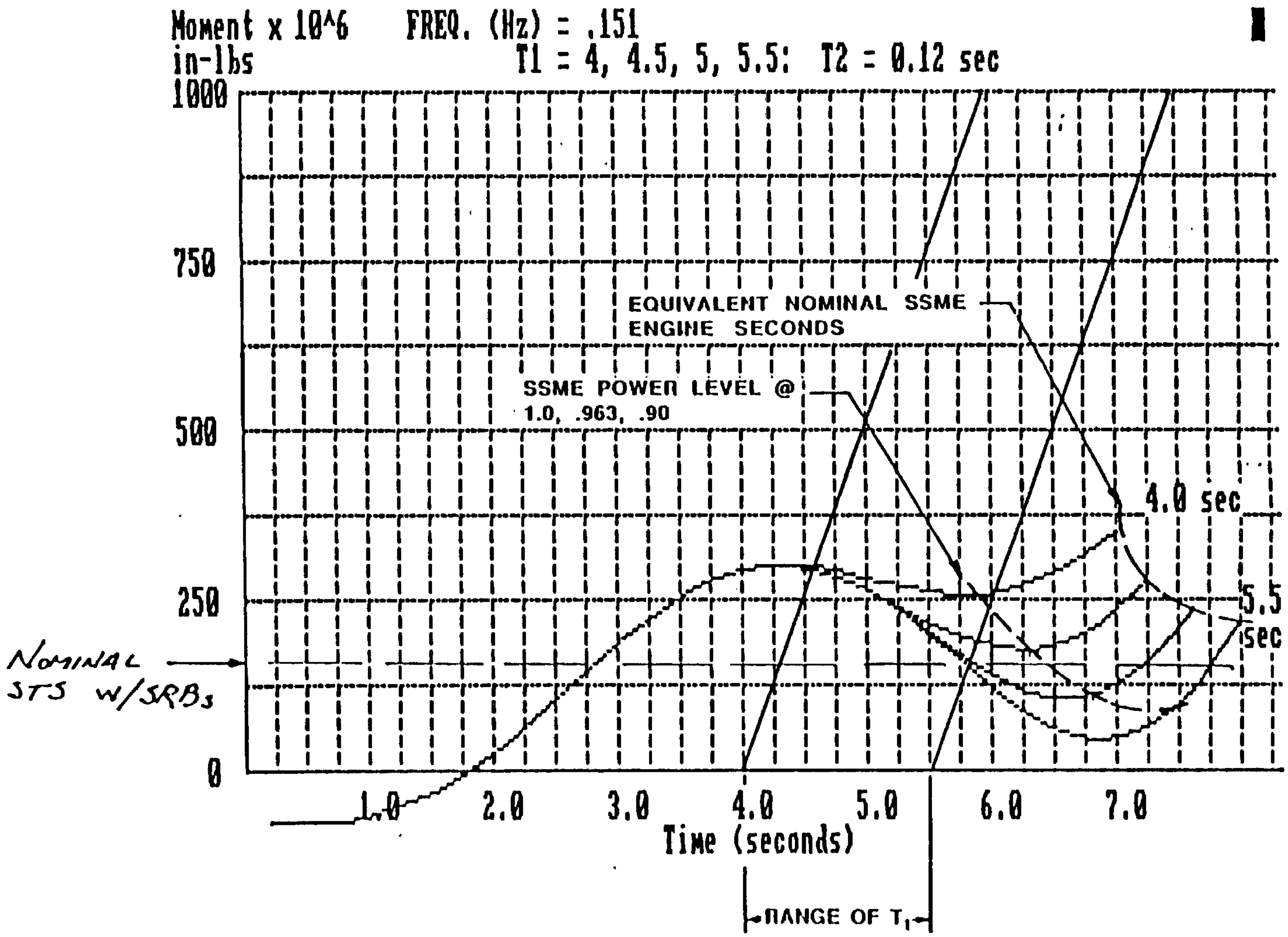


Figure 2.13

# CONFIGURATION RELEASE DATA COMPARISON

| CRITERIA / CONFIG. # | RELIABILITY | | | PERFORMANCE AND SAFETY | | |
|---|---|---|---|---|---|---|
| | MOMENT x $10^6$ | | Δ SSME | Δ SSME | | RELEASE |
| | MAX. | @ REL. | ENG SEC | PROPELLANT | %$RPL_{LRB}$ | TIME |
| NOMINAL SRB | 569 | 145 | NA | NA | NA | 4.382 sec |
| ~~CONFIG #1B~~ | ~~666~~ | ~~145~~ | ~~1.960 sec~~ | ~~-2033 lb~~ | ~~73.0, 50.6~~ | ~~5.035 sec~~ |
| #5D REL #1 | 128 | 128* | -7.280 sec | +7560 lb | 73.1, 58.7 | 1.955 sec |
| ~~#5D REL #2~~ | ~~045~~ | ~~144~~ | ~~7.405 sec~~ | ~~-7600 lb~~ | ~~72.0, 50.4~~ | ~~6.706 sec~~ |
| #1B MOD. T1 (1) | 238 | 141* | -3.831 sec | +3977 lb | 74.1, 59.7 | 5.335 sec |
| #5D MOD. T1 (2) | 300 | 102* | -2.401 sec | +2493 lb | 73.1, 58.7 | 6.835 sec |
| | | | | | | |

* AMPLITUDE AT RELEASE CORRESPONDS TO SSME RPL OF 100, 96.3, AND 90 %

(1) T1 = 3.5 SEC, T2 = 0.12 SEC

(2) T1 = 5.0 SEC, T2 = 0.12 SEC

Fi 9 2.14

### 2.7.1 RELIABILITY

Bending moment magnitudes and Δ SSME engine seconds were assigned to the criteria of reliability since a reduction in these parameters as compared to the nominal SRB configuration could immediately be interpreted as an increase in current STS design margins. A comparison of values for each category indicates that the more compliant configuration #5D is superior to #1B MOD T1 in reducing SSME burn time, and also maximum and minimum bending moments. Configuration #5D MOD T1 is superior only in reducing the minimum bending moment, and thus can be considered the best at reducing twang loads at release. Regardless of relative ranking, all three LRB candidates show a substantial improvement over the stiffer SRB configuration.

### 2.7.2 SAFETY

As noted in Figure 2.13, all remaining candidates meet the requirement for SSME health verification at 90% RPL. In fact, in order to realize the improvements in launch characteristics they require release at 90% of RPL. To delay launch until the last SSME was at 100% of RPL would negate these improvements since these parameters are time dependent and increasing in magnitude at the time of release. STS launch with the SSMEs at these power levels causes the last 10% of thrust to be applied while the vehicle is flying, as oppposed to the current practice of restraining the stack until all engines are up to 100% of RPL. This would require a new engine qualification program to verify SSME safety and function in a new environment.

The question of LRB engine health verification is significant to all LRB configurations since thrust levels at launch are relatively low. This situation is driven by the constraint of T/W =1, where the intent is to reduce the longitudinal lift-off transient . This longitudinal load fluctuation at the SRB/ET thrust fittings occurs when the stack is explosively released from the launch pad and the last two million pounds of thrust are applied (from two SRBs) after release. Instantaneously releasing the stack with T/W $\geq$ 1 would aggrevate this condition by introducng a greater step input to the system, producing longitudinal vibration more severe than the current practice.

Because of this, the LRB engine health verification criteria may become the driving factor in choosing a launch release system and technique. Health verification criteria are constrained by the T/W limitat release, the SSME minimum RPL limit, and the effect of explosive release and the resultant longitudinal transient. If LRB engines require power levels greater than those listed in Figure 2.13 to verify them "Go for Launch" , explosive release becomes impractical because of these constraints. The practice of running LRB engines up to greater thrust levels for health verification, and then throttling back for launch levels would overcome these constraints, but would require an inordinate amount of propellant consumption on the pad, resulting in much larger design capacity, thermal problems from exhaust plumes, and possible performance losses from additional inert tank and structure weight.

### 2.7.3 PERFORMANCE

ET propellant savings could be interpreted as safety criteria for increased capability to close the gaps between intact abort modes , or as additional ascent performance. Since the three remaining configurations do not penalize ET propellant margins of the current Orbiter/ET configuration, no impact to abort margins is realized. As in the case of reliability, all three of the remaining candidates demonstrate a significant improvement in ET propellant margins, with configuration #5D REL #1 providing a substantial savings in ET propellants at more than 7500lbs.

## 3.0 CONCLUSIONS

Trade study conclusons are listed in Figure 2.15. As shown in the transient moment plots for LRB configurations, the SSME ignition sequence can be used to manipulate the resulting transient, minimize the adverse characteristics of the STS launch sequence, and improve propellant margins. While the SSME engline rise time is considered constant at 1.905 sec., the time intervals between engine starts can be varied to produce desirable results without impacting current STS limitations.

Also demonstrated by comparison, when the half wave-length of the system increases beyond the SSME rise time, the response time increases, allowing greater SSME thrust to build up before bending moment limits are exceeded. Thus, the more compliant booster configuration is advantageous to controlling and reducing the transient loads and twang.

The constraints on T/W and the resulting low LRB thrust levels at release may present an insurmountable problem for explosive release techniques. Issues of control authority and collision avoidanced near launch pad hardware, health verification at low thrust, and the risks of launching with propulsion systems operating below nominal levels will be difficult to resolve. Coupled with the difficulties of duplicating launch environments for LRB and new SSME engine qualification programs, these issues may preclude the use of explosive launch release altogether.

## 4.0 RECOMMENDATIONS

Trade study recommendations are listed in Figure 2.16. If the issues associated with low LRB thrust levels can be resolved, it is recommended that investigation of transient manipulation and explosive release techniques continue for LRB configurations. Options other than ignition sequence timing and stiffness reduction remain to be explored. Investigation of SSME rise time variation and the impact to STS operations is recommended as a first alternative. The feasibility of tilting the stack (on the launch pad) back in the X-Z plane such that the CG moment arm for the Orbiter/ET mass contributes greater resistance to the off-set SSME thrust should also be investigated.

If the issues of LRB thrust levels at release cannot be resolved satisfactorily, it is recommended that a damped launch release system similar in function to those used for Saturn and Atlas launch vehicles be adopted. This type of system could be superior in reducing base bending moments and vibratory twang loads at release, while providing gradual vehicle release as thrust builds up to flight levels.

LRB
LIQUID ROCKET BOOSTER STUDY

# TRADE STUDY 1.10 CONCLUSIONS

1. SSME IGNITION SEQUENCE CAN BE OPTIMIZED TO MINIMIZE BOLT LOAD AND TWANG, AND IMPROVE LIFT PERFORMANCE.

2. COMPLIANT BOOSTER IS ADVANTAGEOUS FOR CONTROLLING TRANSIENT EFFECTS ON BOLT LOADS AND TWANG WITH SSME SEQUENCE TIMING.

3. LOW BOOSTER RPL (58%-73%) AT RELEASE, AND "SLOW" RISE TIME MAY PRECLUDE EXPLOSIVE LAUNCH RELEASE TECHNIQUE WITH LRBs.

   - CONTROL AUTHORITY NEAR PAD
   - HEALTH VERIFICATION
   - EMOTIONAL ISSUES

F re 2.15

# TRADE STUDY 1.10 RECOMMENDATIONS

1. IF BOOSTER RPL AND RISE TIME ISSUES CAN BE RESOLVED, PROCEED WITH EXPLOSIVE RELEASE OPTIMIZATION
   - IGNITION SEQUENCE
   - REDUCED STIFFNESS
   - ENGINE RISE TIME
   - TILTED STACK

2. IF ISSUES CANNOT BE RESOLVED, BASELINE DAMPED LAUNCH RELEASE SYSTEMS FOR LRB.

Figure 2.16

UPDATE ON T.S. 1.10 IGNITION SEQUENCE

Since this initial trade study was performed, a dynamic loads model was developed and a first cut made of loads and deflections. Our basic philosophy continues to be:

1) A soft LRB is acceptable, even preferable when

2) SSME starts are staggered about 4 seconds and

3) The whole stack is held down until all engines (Orbiter and LRBs) exceed 90% of full thrust (allowing time to determine engine health and then

4) A controlled, "slow" release occurs. There is probably insufficient room for Saturn type release heads. Therefore we are considering explosive bolts + stretch bolts drawn out about 6" through a die.

This concept appears to have many advantages including lower deflections and less twang than the current STS system with SRM.

TRADE STUDY 1.13

# RECOVERY ANALYSES
# AND
# SELECTIONS

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# LRB DOWNSELECTION MEETING 2/5/88

LRB

**MEETING OBJECTIVE:** Downselect Recovery/Reusability Concepts for LRB

**LRB BACKGROUND:** LRB for STS Systems Study, NAS 8-37137

- ATP 10/13/87
- Technical completion 6/13/88

MMC

- Baselining storable propellants
- Have included LOX/RP-1

GDSS Downselected from 15 concepts to 5 in January

- Two existing engines (SSME, F-1)
- Two new pump-fed engines (LOX/RP-1, LOX/LH2)
- One pressure-fed engine (LOX/RP-1)

Subsequently dropped F-1 concept option

Downselection to be completed by next IPR

8803/

# LRB RECOVERY DOWNSELECTION MEETING

LRB

## RECOVERY

## REFURBISHMENT

## REUSE

## ANALYSIS, IMPACTS, & SELECTIONS

**TOPICS:**

- Objectives & Proposed Options
- Methodology
- Recovery Concepts & Methods
- Technological Downselections
- Selected Recovery Techniques
- Recovery Options Evaluations
- Weight Impacts
- Cost Comparisons
- Conclusions & Recommendations

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# TRADE 1.4
# DEGREE OF RECOVERY/REUSABILITY

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**LRB**

**OBJECTIVE:**

Determine the technical and cost feasibility for recovery, refurbishment, and reuse of a total LRB or the propulsion/avionics (P/A) portion.

**BASIC GROUNDRULES/ASSUMPTIONS/GUIDELINES:**

- Booster design will use multiple engines per booster
- Recovery may be downrange with limited exposure of components to salt water
- Recovery may be by dry landing, either downrange or return to launch site
- Number of boosters required per year will be 9X2=18
- Number of engines required per year will be 18X4=72
- Performance of LEO maintained
- Maintain one engine-out abort capability

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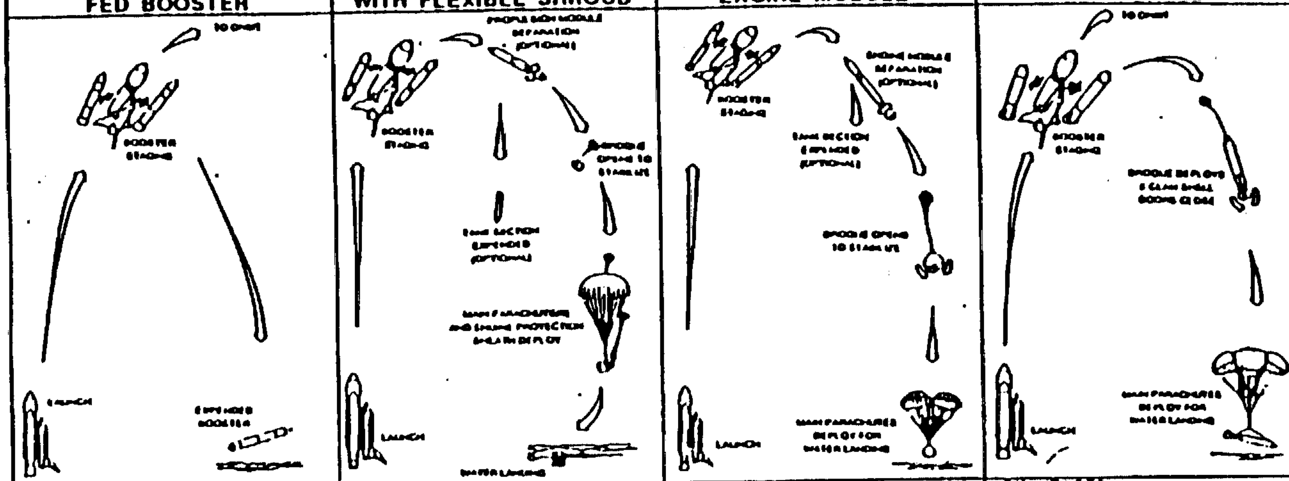
# GD/SS PROPOSED RECOVERY OPTIONS
## (PAGE 1 OF 2)

LRB



| EXPENDABLE PRESSURE-FED BOOSTER | PROPULSION MODULE WITH FLEXIBLE SHROUD | CANNONBALL ENGINE MODULE | FULL RETURN WITH CLAM SHELL |
| --- | --- | --- | --- |
| ***ADVANTAGES:***<br>• NO TURBOMACHINARY (WARM GAS PRESSURANT)<br>• STRONG, THICK WALLED TANKS MAY ALLOW WATER RECOVERY AS AN OPTION<br>• OCEAN-GOING REC. FORCE NOT REQ'D.<br>• DDT&E - LOW<br>***DISADVANTAGES:***<br>• ADDED FACILITIES TO SUPPLY PRESSURIZATION<br>• WEIGHT PENALTY IN TANK STRUCTURE<br>• SIZE MAY IMPACT ATTACH. TO PAD & VEHICLE DUE TO ENGINE CLUSTER<br>• RELATIVELY LOW PERFORMANCE<br>• HIGH COST RISK IF UNIT COST PROJECTIONS ARE NOT ACHIEVED | ***ADVANTAGES:***<br>• REUSE OF HIGHEST COST BOOSTER ELEMENT (ENGINES)<br>• MINIMAL IMPACT TO PAD & VEHICLE<br>• NO SALT WATER ON ENGINES<br>• USES EXISTING WATER RECOVERY EQUIPMENT<br>• POTENTIALLY LIGHTWEIGHT SYSTEM<br>• DDT&E COST - LOW<br>***DISADVANTAGES:***<br>• OCEAN GOING RECOVERY FORCE REQ'D.<br>• PROCESSING TIME TO REFURBISH<br>• RECOVERY ATTRITION RATE<br>• POTENTIAL FOR SALT WATER CONTAMINATION | ***ADVANTAGES:***<br>• REUSE OF HIGHEST COST BOOSTER ELEMENT (ENGINES)<br>• MINIMAL IMPACT TO PAD & VEHICLE<br>• NO SALT WATER ON ENGINES<br>• USES EXISTING WATER REC. EQUIP.<br>• DDT&E COST - LOW<br>***DISADVANTAGES:***<br>• WEIGHT HIGHER THAN SHEATH<br>• LARGE DIA. DRAG INDUCING POD REQ'D TO ENCLOSE CLUSTERED ENGINES<br>• OCEAN GOING RECOVERY FORCE REQ'D<br>• PROCESSING TIME TO REFURBISH<br>• RECOVERY ATTRITION RATE | ***ADVANTAGES:***<br>• RECOVERS ENTIRE BOOSTER<br>• SIMILAR RECOV. PROCEDURES TO SRBs<br>• MINIMAL IMPACT TO PAD & VEHICLE (DEPENDING ON ENGINE CLUSTER SIZE)<br>• NO SALT WATER ON ENGINES<br>***DISADVANTAGES:***<br>• ENTIRE BOOSTER DESIGNED FOR WATER IMPACT (WEIGHT PENALTY)<br>• LARGE DIA. DRAG INDUCING CLAM SHELL DOORS REQ'D FOR CLUSTERED ENGINES<br>• OCEAN GOING RECOVERY FORCE REQ'D<br>• POTENTIALLY HIGHEST RECOVERY ATTRITION RATE<br>• LARGE REFURBISHMENT COST<br>• RESTARTING PRODUCTION LINE FOR BOOSTER REPLACEMENT |

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# GD/SS PROPOSED RECOVERY OPTIONS
## (PAGE 2 OF 2)

LRB

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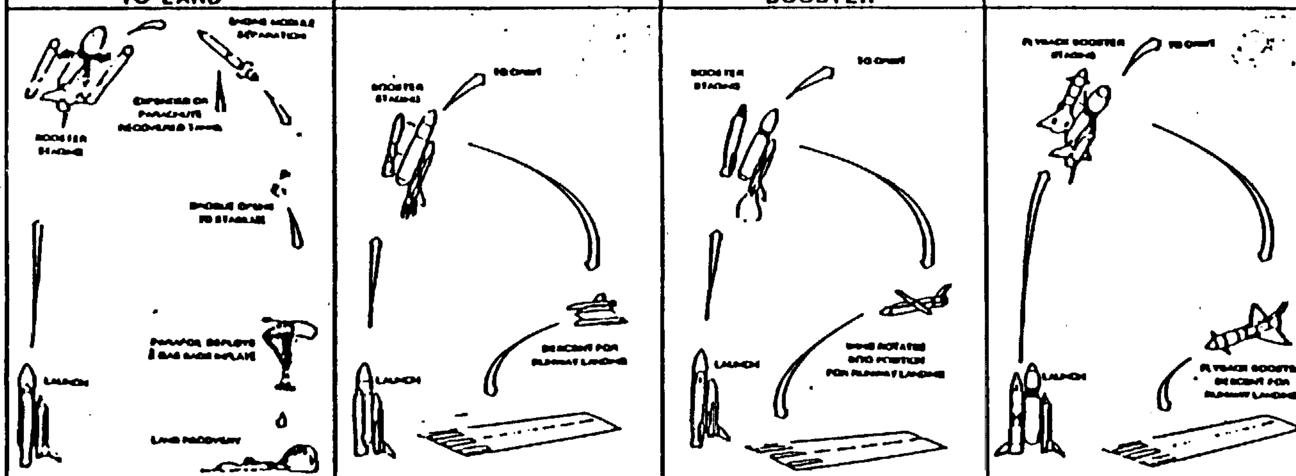

| PARAFOIL RECOVERY TO LAND | * CATAMARAN BOOSTER | ROTATING/SWING WING BOOSTER | * FLYBACK BOOSTER |
|---|---|---|---|
| ADVANTAGES:<br>• NO OCEAN-GOING RECOVERY FORCE<br>• REUSE OF HIGHEST COST BOOSTER ELEMENT (ENGINES)<br>• MINIMAL IMPACT TO PAD & VEHICLE<br>• LESS LOSSES THAN WATER RECOVERY<br>• NO RISK OF SALT WATER CONTAMINATION<br>DISADVANTAGES:<br>• GUID/NAV & ACTIVE CONTROL REQ'D<br>• RANGE SAFETY ISSUES<br>• LIKELY HEAVIER THAN WATER RECOVERED CONCEPTS<br>• REQUIRES LAND RECOVERY SUPPORT INFRASTRUCTURE<br>• REQUIRES TRAJECTORY MODIFICATIONS OR TOSSBACK MANEUVER | ADVANTAGES:<br>• FULLY REUSABLE<br>• NO OCEAN GOING RECOVERY FORCE<br>• MINIMAL IMPACT TO PAD & VEHICLE<br>• FEW RECOVERY LOSSES<br>• LANDS ON EXISTING RUNWAYS<br>• RECURRING COST - POTENTIAL FOR LOWEST PER FLIGHT<br>DISADVANTAGES:<br>• GUIDANCE/NAV REQUIRED<br>• RANGE SAFETY ISSUES<br>• RESTARTING PRODUCTION LINE FOR BOOSTER REPLACEMENT<br>• DDT&E COST - HIGH | ADVANTAGES:<br>• FULLY REUSABLE<br>• NO OCEAN GOING REC. FORCE REQ'D<br>• FEWEST RECOVERY LOSSES<br>• MINIMAL IMPACT TO PAD & VEHICLE<br>• RECURRING COST - POTENTIALLY LOWEST PER FLIGHT<br>DISADVANTAGES:<br>• ROTATING/SWING WING REPRESENTS POSSIBLE SINGLE POINT FAILURE<br>• GUIDANCE/NAV CONTROL REQ'D.<br>• RANGE SAFETY ISSUES<br>• RESTARTING PRODUCTION LINE FOR VEHICLE REPLACEMENT<br>• SIMULTANEOUS VEHICLE LANDINGS REQUIRE MULTIPLE RUNWAY FACILITY<br>• DDT&E COST - HIGH | ADVANTAGES:<br>• EASILY EVOLVES TO ALS CONFIG'D. FBB<br>• FULLY REUSABLE<br>• NO OCEAN-GOING REC. FORCE REQ'D<br>• FEWEST RECOVERY LOSSES<br>• LANDS ON EXISTING RUNWAYS<br>• RECURRING COST - POTENTIALLY LOWEST PER FLIGHT<br>DISADVANTAGES:<br>• MAJOR CHANGES REQ'D. TO PAD & I/Fs<br>• CHANGES TO STS FLIGHT PROFILE<br>• INCOMPATIBLE WITH SRBs<br>• GUIDANCE/NAV CONTROL REQ'D.<br>• RANGE SAFETY ISSUES<br>• RESTARTING PRODUCTION LINE FOR VEHICLE REPLACEMENT<br>• DDT&E COST - HIGH |

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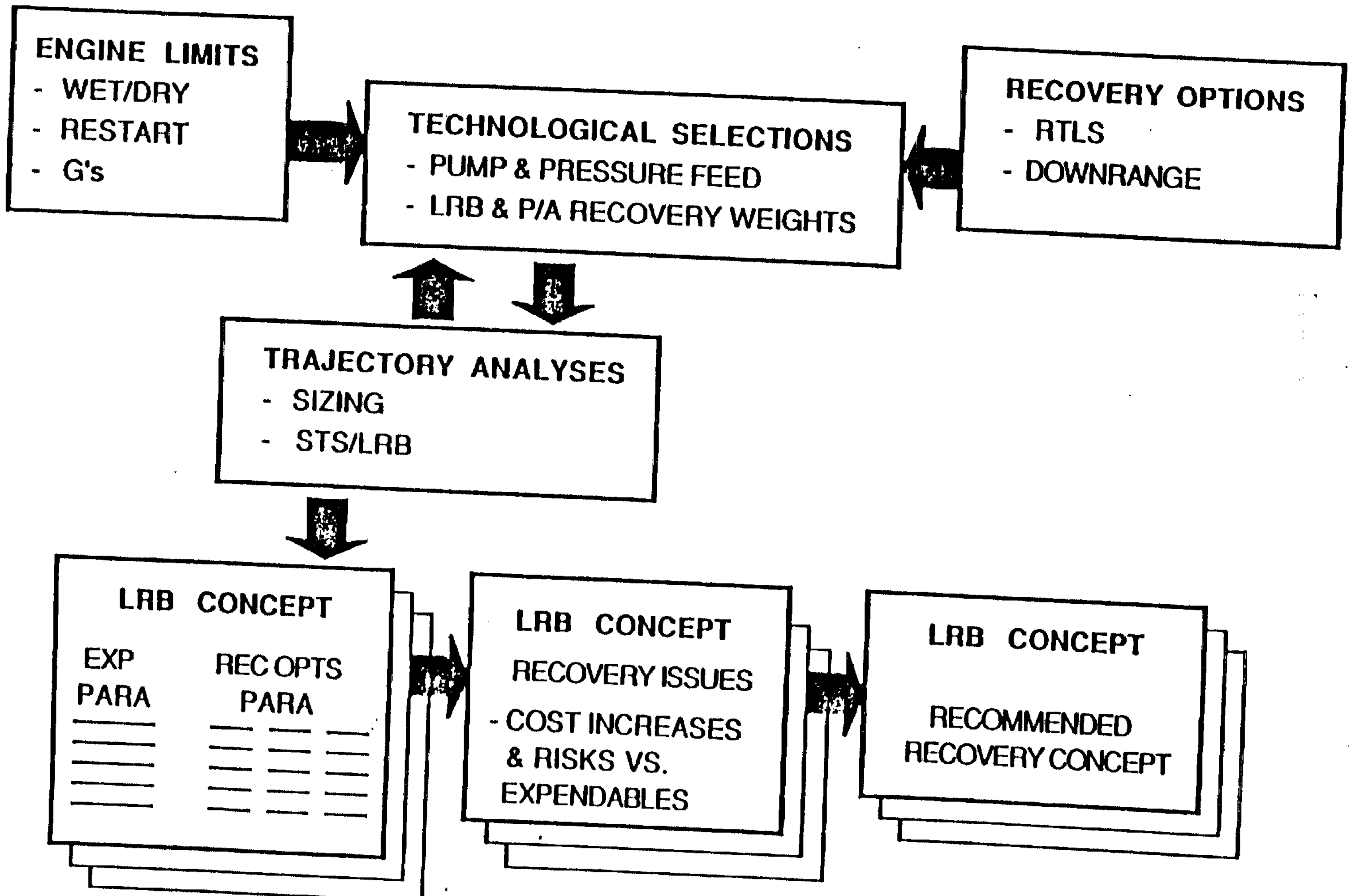
*REQUIRES TURBOJET SYSTEMS-RELEGATED TO GROWTH OPTIONS

# LRB RECOVERY DOWNSELECT METHODOLOGY

LRB

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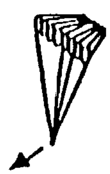
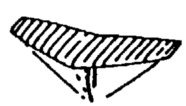
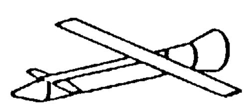
# STOWABLE / DEPLOYABLE RECOVERY CONCEPTS

**LRB**

| RECOVERY SYSTEM | LIFT / DRAG | CHARACTERISTICS |
|---|---|---|
| PARACHUTE  • SINGLE • CLUSTER | 0 | IN USE, WELL DEFINED, USED ON SRM, etc. |
| RAM AIR  | 3 | REQUIRES MANY SHROUD LINES. CURRENT TECHNOLODY LIMITED DUE TO REEFING PROBLEMS WHEN RECOVERING WEIGHTS OVER 20,000 LBS. |
| INFLATABLE WING  • ROGALLO • HANG GLIDER • PARAWING (SEMI RIGID) | 3 - 7 | ROGALLO AND HANG GLIDER TECHNOLOGY ESTABLISHED BUT HEAVY LIFT CAPABILITY UNKNOWN. SEMI-RIGID PARAWING ANALOGOUS TO RIGID WING, CAN WITHSTAND HIGH LOAD, WILL REQUIRE DEVELOPMENT. |
| SWING OUT RIGID WING  | 10 | BASIC AIRCRAFT WING DESIGN. SWING OUT REQUIRES DEVELOPMENT. |

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# RECOVERY METHODS TREE

**LRB**

- METHOD LRB & P/A
  - RTLS
    - TOSSBACK GLIDE
      - RIGID WING
      - PARAWING
    - TOWBACK
      - RIGID WING
      - PARAWING
    - ~~AIR SNATCH~~
    - ~~JET FLYBACK~~
  - DOWNRANGE
    - GLIDE
      - PARAWING
    - BALLISTIC ($H_2O$)
      - PARACHUTE

## CRITERIA

- Technological
- Risk
- Operations
- Cost

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# TECHNOLOGICAL TRADE TREE

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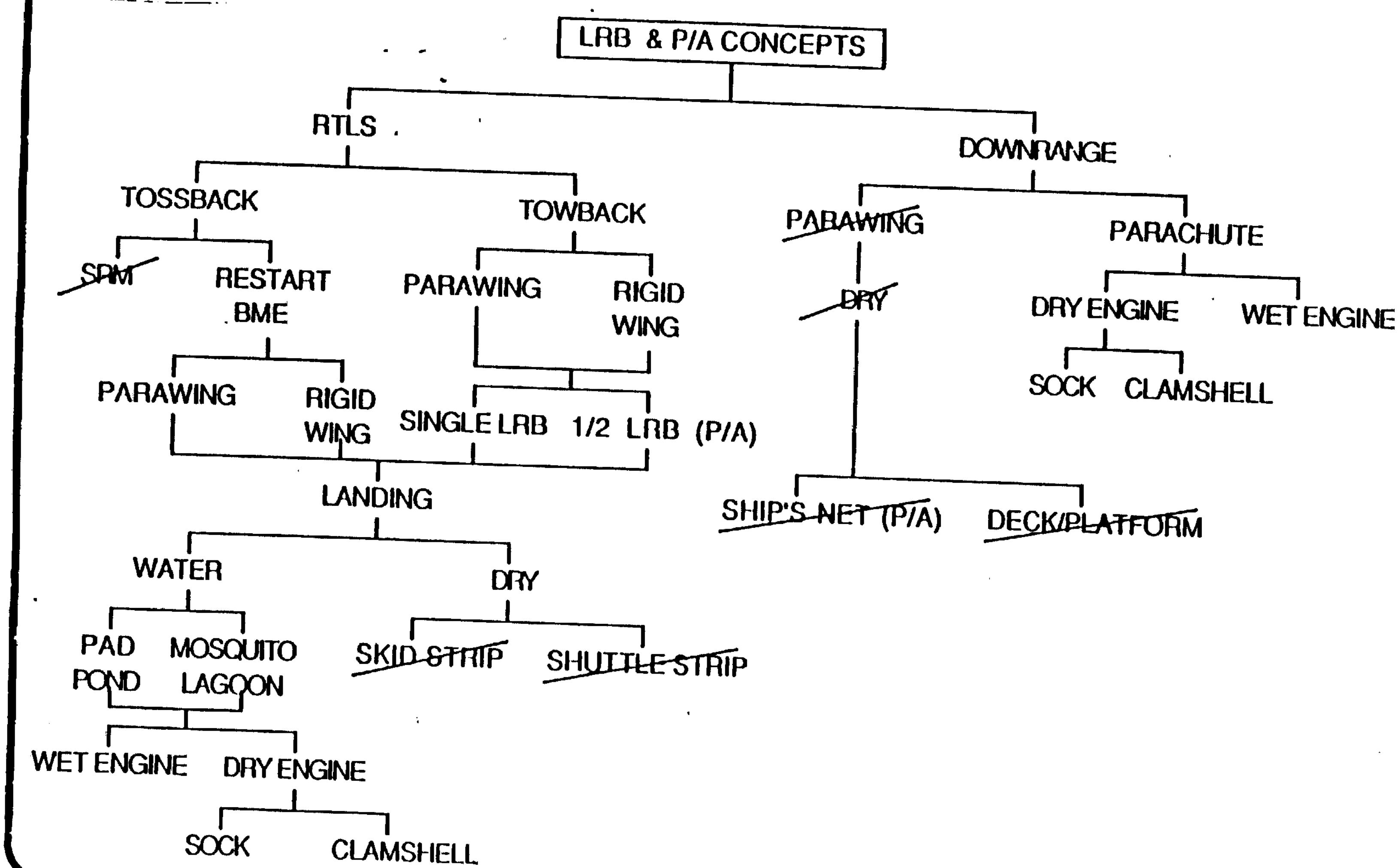


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# RECOVERY TECHNOLOGICAL DOWNSELECT PHILOSOPHY

## LRB

**CONSIDER RECOVERY OF.....**

- LRB, for total re-use
- Partial LRB, for P/A module recovery
- P/A module only, not practical:
  - structural weight high for impact shielding
  - complicated separation
  - use planned discarded LRB tanks

**ENGINE & P/A ALLOWANCES**

- Engine and P/A in water - O.K.
  - New engines can be designed for minimum refurbishment from water
  - Dry cover (clamshell, sock) is only cost effective for SSME
- Impact to 5g

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# P/A MODULE CONCEPT

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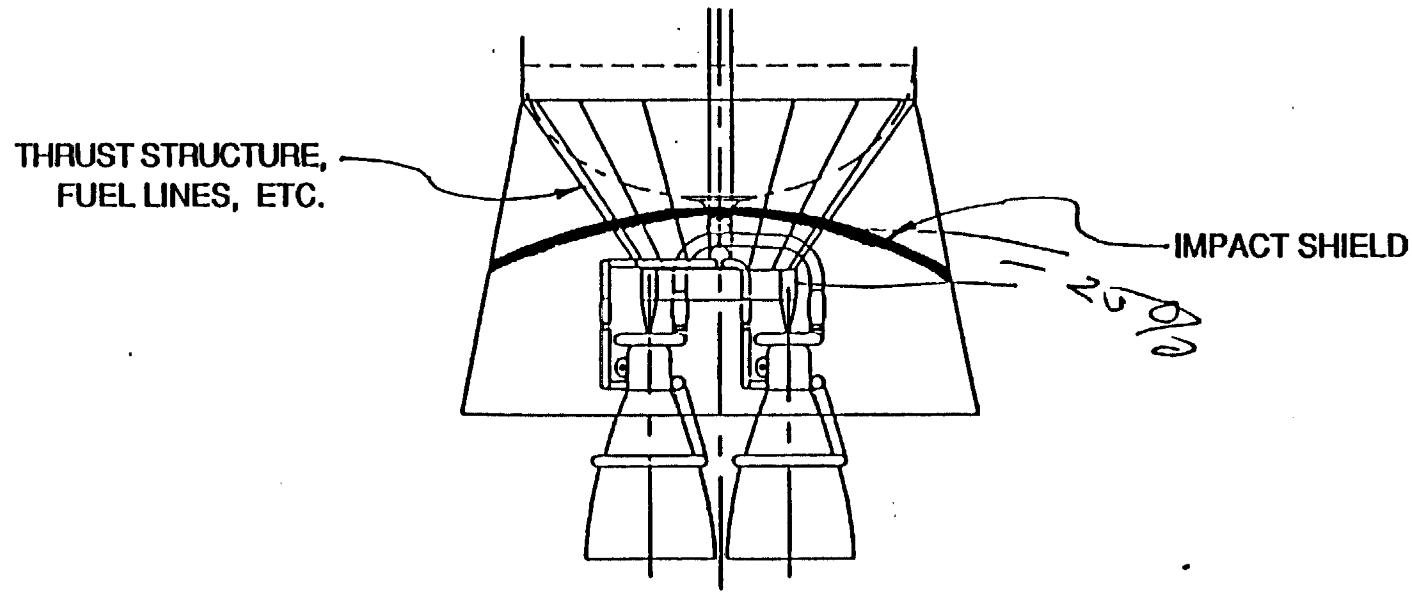


NOTES:
- MUST DISCONNECT ALONG SHIELD
- WEIGHT INCREASE = 1.35 * WEIGHT OF THRUST STRUCTURE

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# RECOVERY TECHNOLOGICAL DOWNSELECT PHILOSOPHY (continued)

## LRB

**RTLS OPTIONS**

- Toss-back to RTLS
  - Restart BME (50% thrust)
  - SMR's too heavy
- Tow-back, via large fixed wing airplane
  - LRB with rigid wing
  - LRB with parawing (developed by UTC)
  - Partial LRB with parawing, for P/A
  - Runway landing, not practical because the landing gear would be too heavy and complicated, also there would be limited descent crossrange control
  - Placid inland water landing - O.K.

**DOWNRANGE OPTIONS**

- Platform (or ship's deck), not practical for same reasons stated in the runway landing option
- Parachutes, versus wings, provide lightest and lowest impact speeds
- LRB (total) pump-fed, not practical because the parachute/retrorocket weights would be too high for soft landing and rough seas overstress the tanks
- LRB (total) pressure-fed, is practical with parachutes
- Partial LRB to save P/A module, with parachutes

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# TECHNOLOGICAL DOWNSELECTED RECOVERY CONCEPTS

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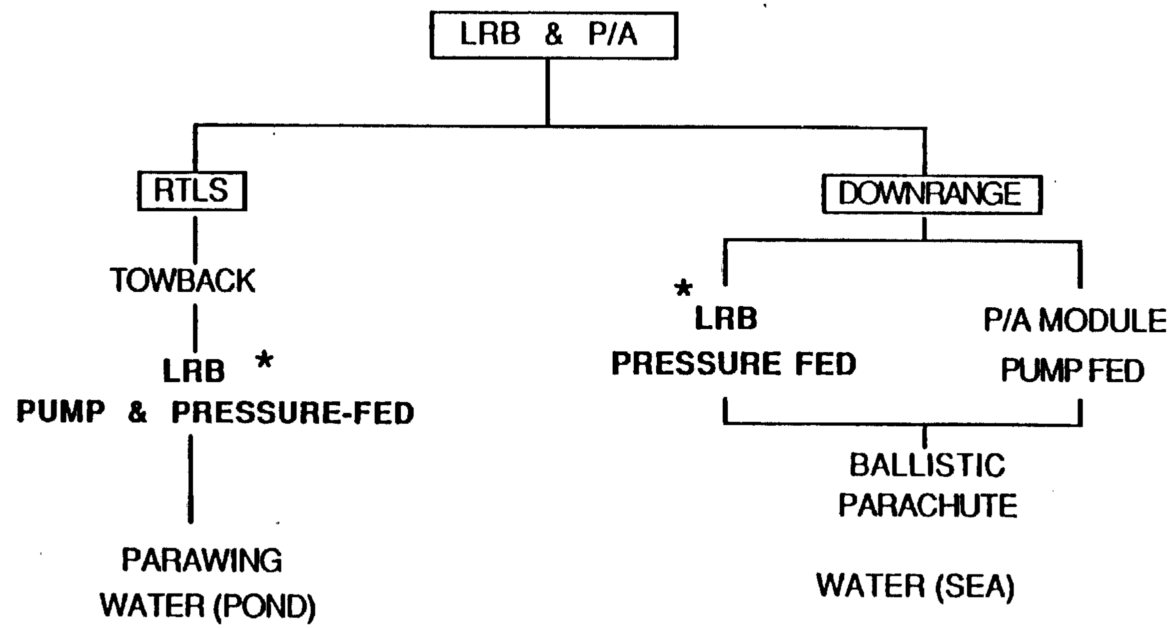


* MOST DESIRABLE CONCEPT; LEAST COMPLEXITY

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# TRAJECTORY GUIDELINES

LRB

**ASCENT**

- Established trajectory profile, fixed MECO conditions
- 75,500 pounds payload to 150 NM orbit
- Engine-out at lift-off - 1.10 g

**POST-SEPARATION**

- Ballistic to RTLS tow-back and to downrange
- RTLS by toss-back and glide-back
  - BME (50%) shortly after separation

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# Trajectory Ground rules

Ascent Constraints

- Maximum Q*alpha: -3000 pounds-degree/foot**2
- Maximum Dynamic pressure: 750 pounds/foot**2
- Angle of attack:
  1.05 <= mach <= 1.55; -5 <= angle of attack <= -4
- Engine out Abort on pad thrust/weight: 1.1

MECO Conditions

- Velocity: 25,670 feet/second
- Flight Path Angle: 0.65 degrees
- Altitude: 57 nautical miles
- Orbital Inclination: 28.5 degrees
- Payload weight: 75,500 pounds

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# TOSSBACK RTLS

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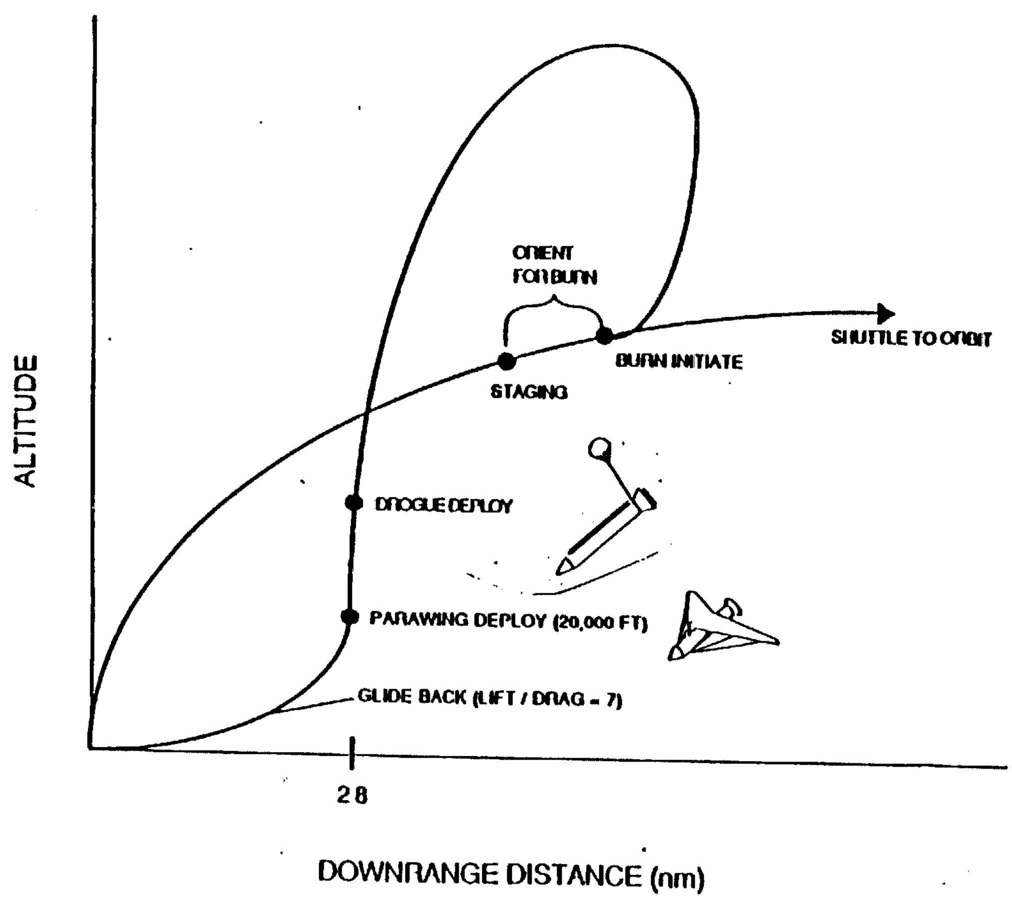


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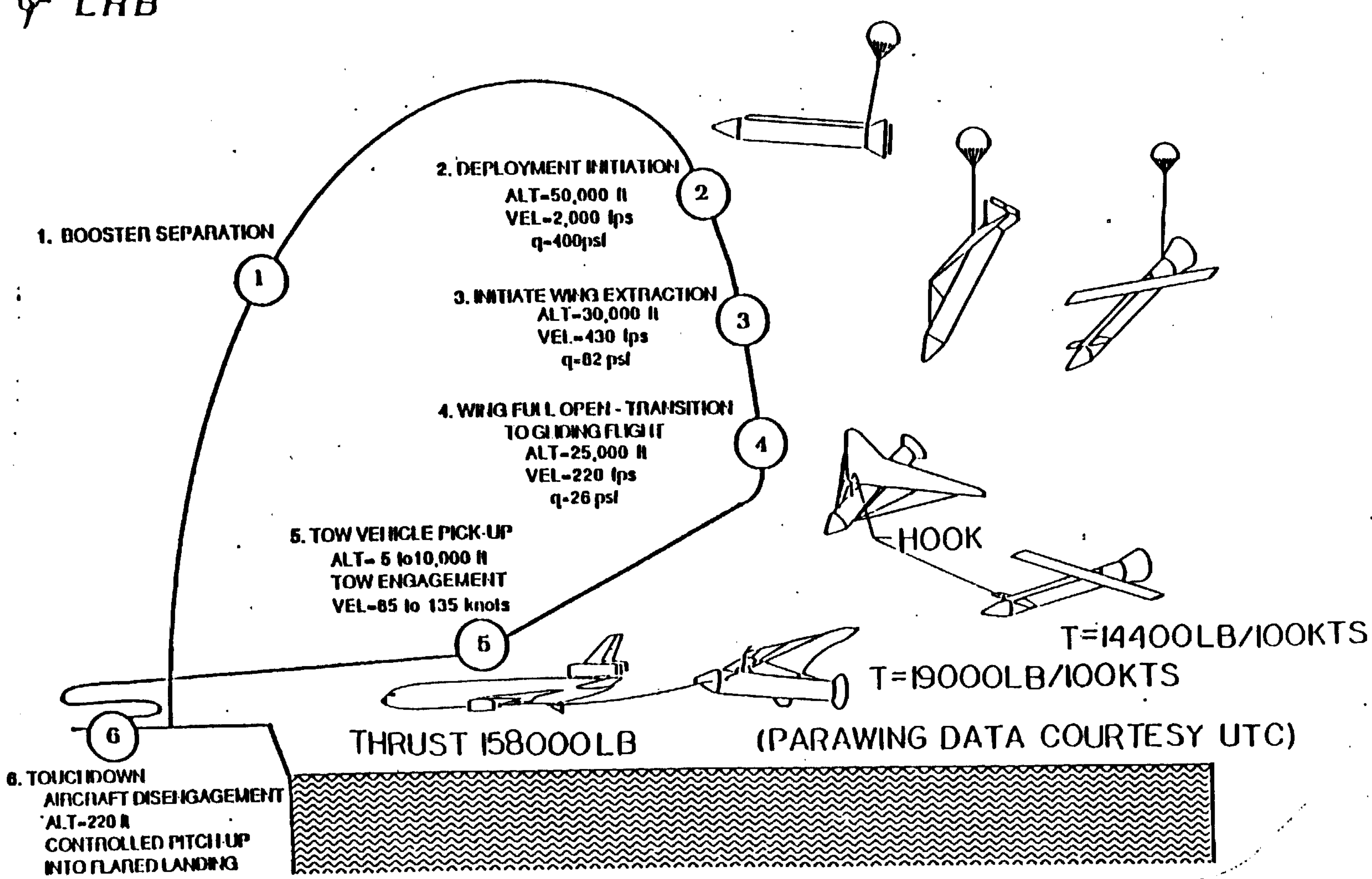
# TOWBACK
## DEPLOYABLE WING CONCEPT
## PARAWING & RIGID WING LRB

LRB



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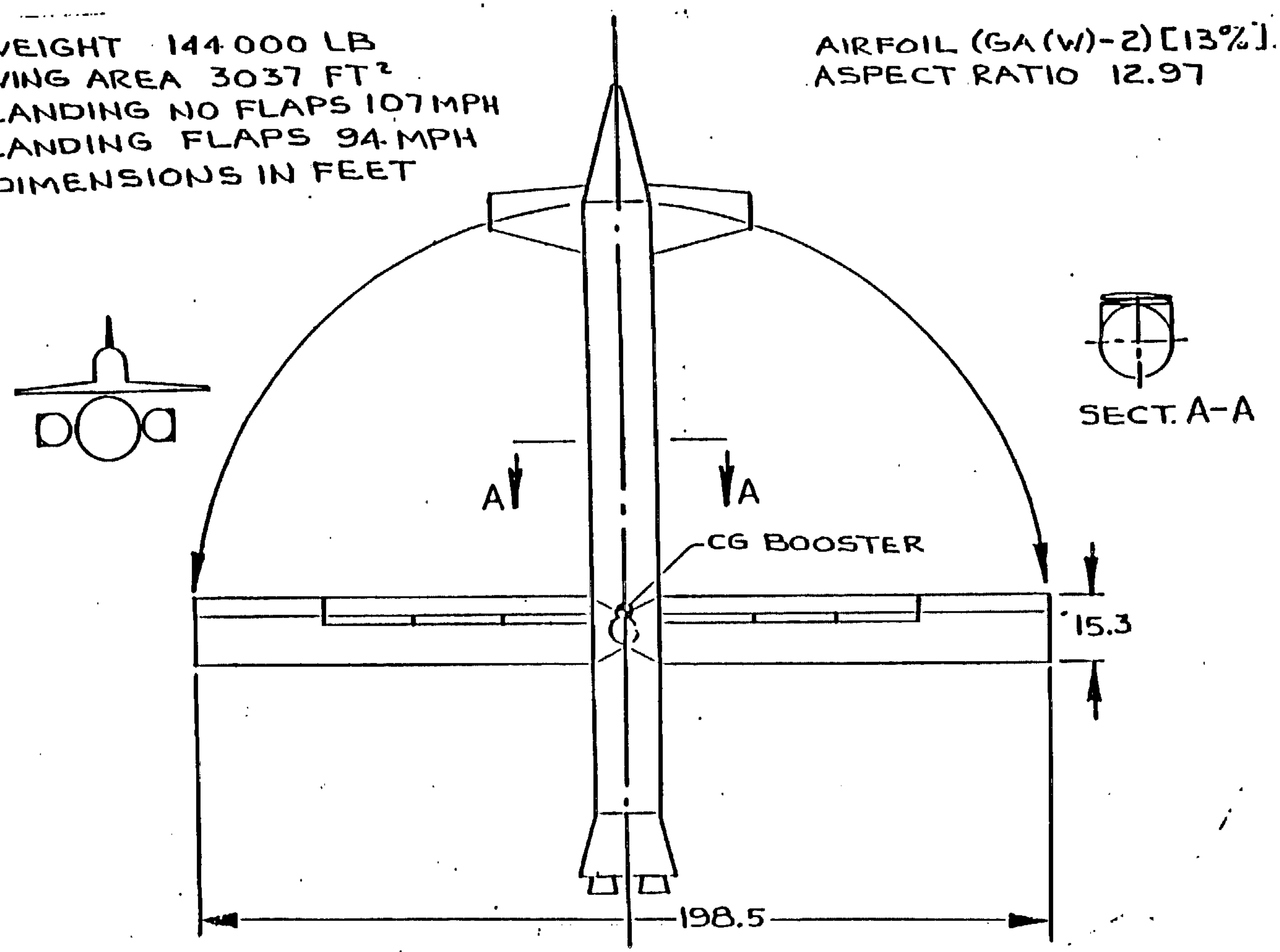
# LRB WITH RIGID WING

**LRB**

WEIGHT 144 000 LB
WING AREA 3037 $FT^2$
LANDING NO FLAPS 107 MPH
LANDING FLAPS 94 MPH
DIMENSIONS IN FEET

AIRFOIL (GA(W)-2) [13%]
ASPECT RATIO 12.97

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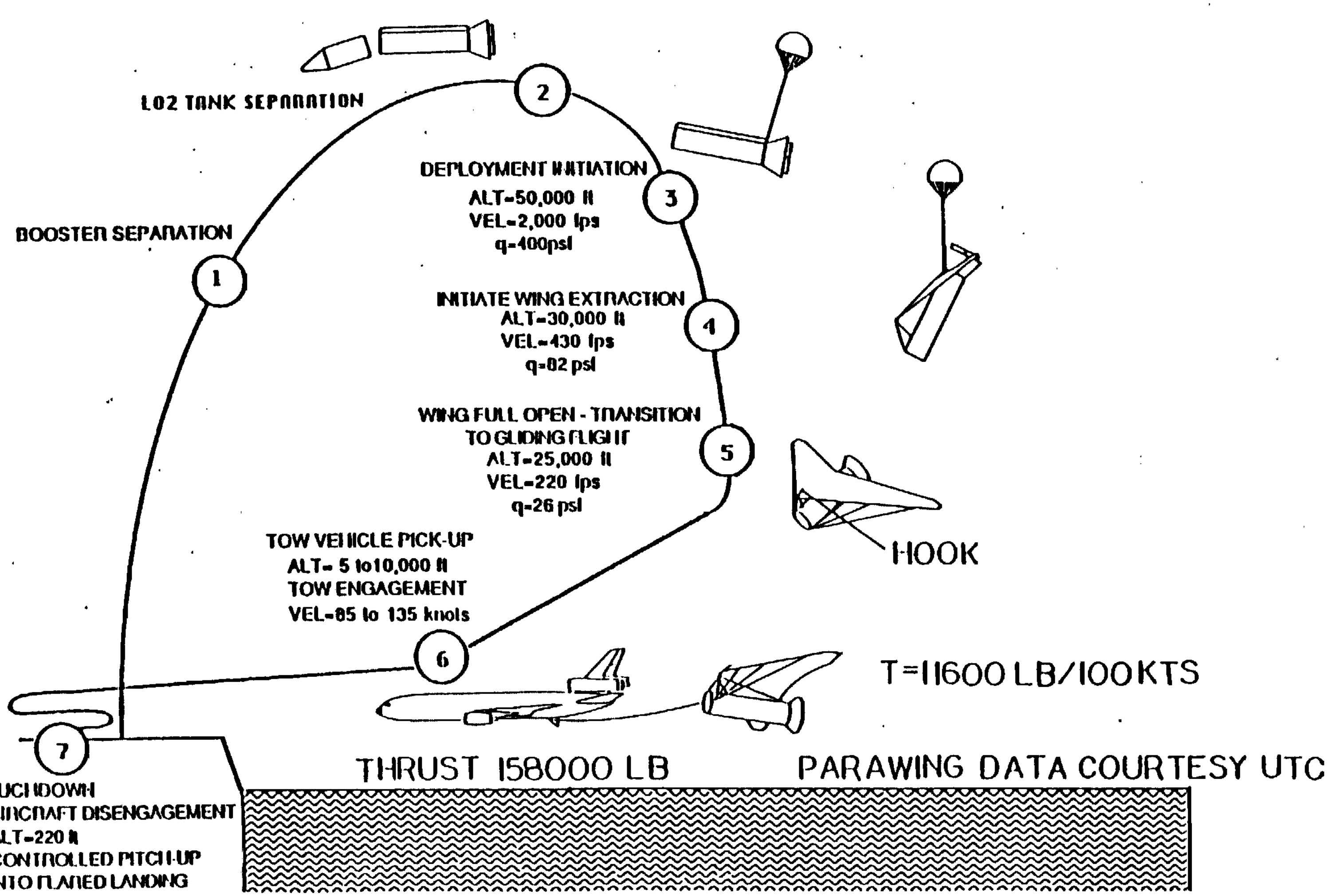
# TOWBACK
# DEPLOYABLE WING CONCEPT
# PARAWING 1/2 LRB (P/A)

LRB



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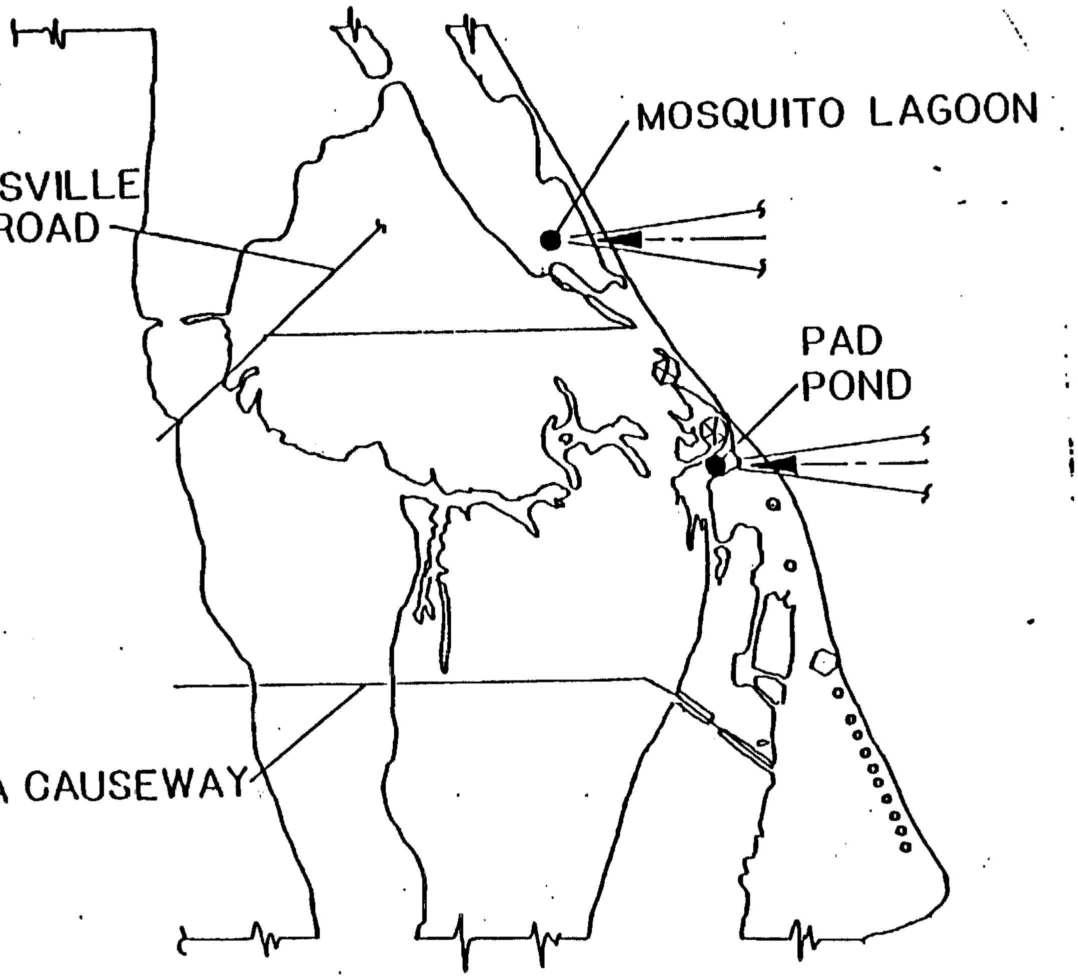
# RTLS PLACID WATER LANDING SITE

LRB

## LRB GLIDE LANDING AT CAPE



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# DOWNRANGE PARACHUTE RECOVERY

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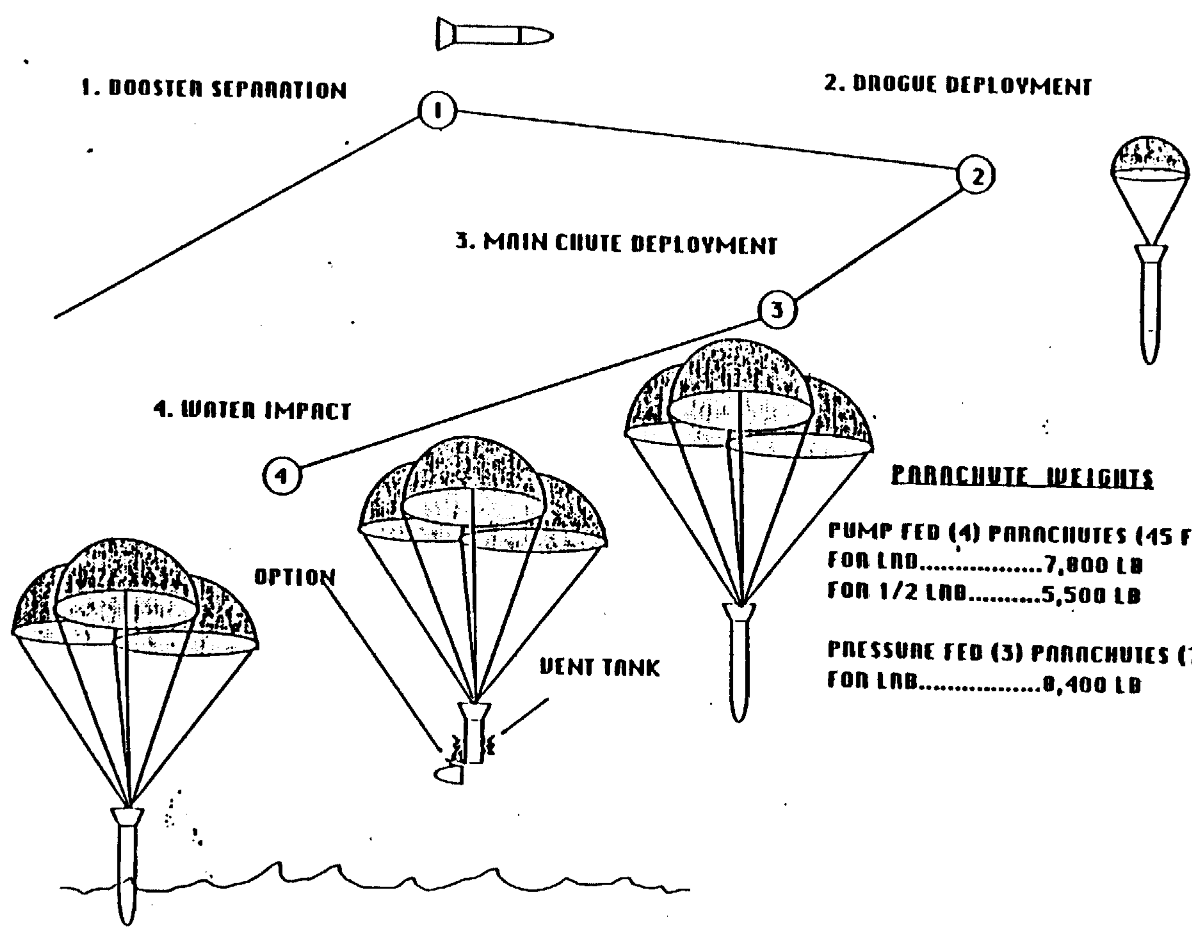



**PARACHUTE WEIGHTS**

PUMP FED (4) PARACHUTES (45 FT/SEC)
FOR LRB..................7,800 LB
FOR 1/2 LRB..........5,500 LB

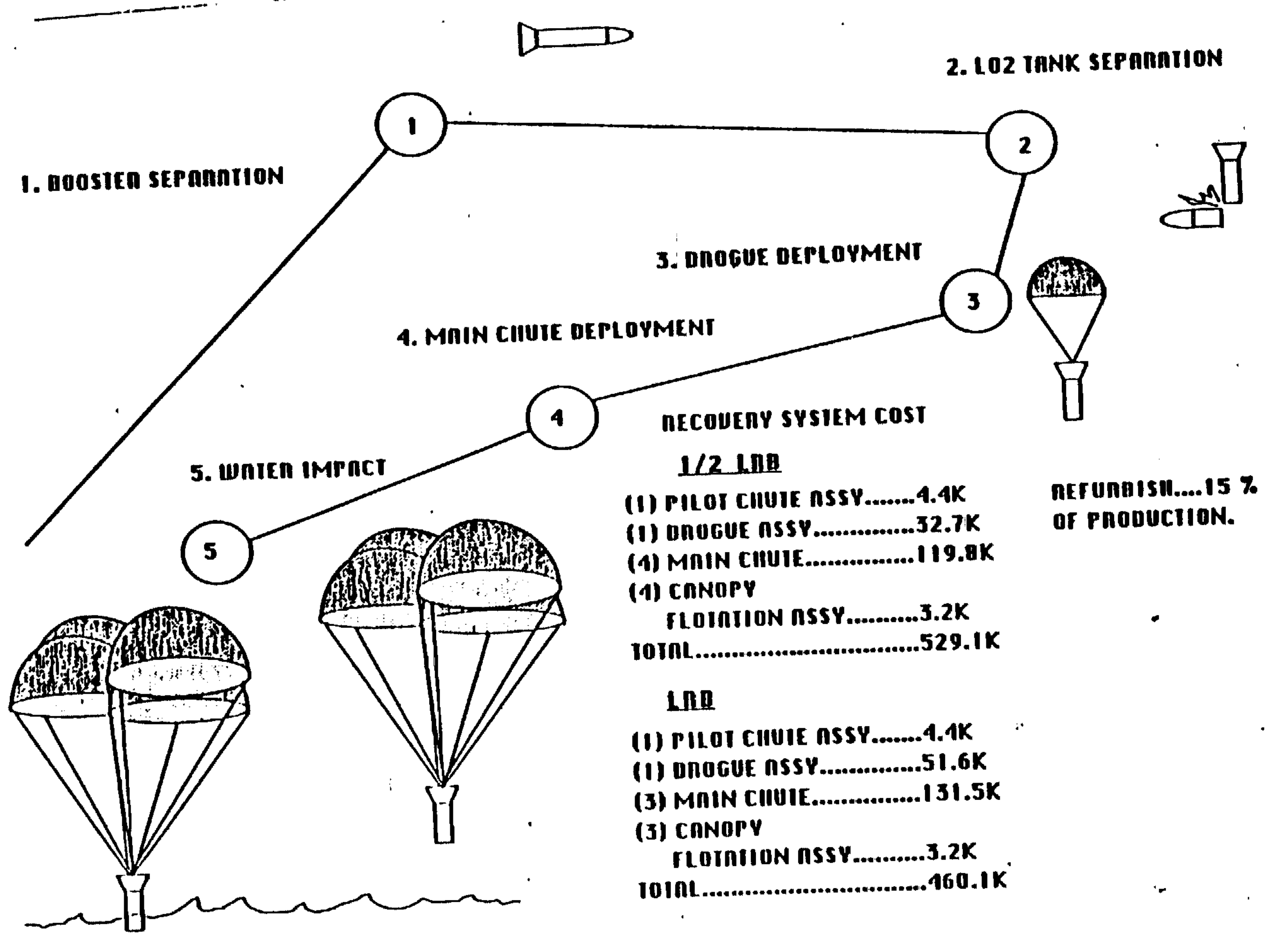
PRESSURE FED (3) PARACHUTES (74 FT/SEC)
FOR LRB.................8,400 LB

GENERAL DYNAMICS
Space Systems Division

# DOWNRANGE PARACHUTE, 1/2 LRB RECOVERY WITH 1/2 LRB AND LRB COST

## BACK-UP (5)

LRB




RECOVERY SYSTEM COST

1/2 LRB

(1) PILOT CHUTE ASSY.......4.4K
(1) DROGUE ASSY..............32.7K
(4) MAIN CHUTE...............119.8K
(4) CANOPY
FLOTATION ASSY..........3.2K
TOTAL...............................529.1K

LRB

(1) PILOT CHUTE ASSY.......4.4K
(1) DROGUE ASSY..............51.6K
(3) MAIN CHUTE...............131.5K
(3) CANOPY
FLOTATION ASSY..........3.2K
TOTAL...............................460.1K

REFURBISH....15 % OF PRODUCTION.

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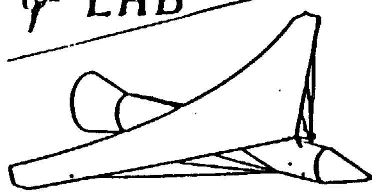
# SELECTED STOWABLE RECOVERY SYSTEMS WEIGHT AND COST

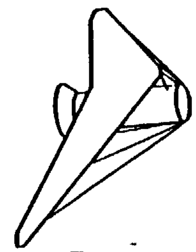
BACK-UP (6)

PARAWING

PUMP FED
RECOVERY SYSTEM
WEIGHT.....7,370 LB
COST.........4.5M

PRESSURE FED
RECOVERY SYSTEM
WEIGHT.....11,179 LB
COST.........6.8M

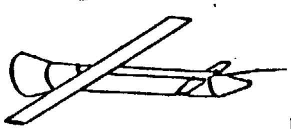


PARAWING

PUMP FED (1/2 LRB)
RECOVERY SYSTEM
WEIGHT.....4,702 LB
COST.........4M

PARAWING REUSABLE HARDWARE

| ITEM | # OF USES |
|---|---|
| PARAWING CANOPY/SAIL | 15 |
| AIR FRAME STRUCTURE | (SAME AS PAYLOAD) |
| DEPLOYMENT ACTUATORS | 10 |
| DROGUE CHUTE AND RISERS | 6 |



SEMI-RIGID WING

PUMP FED
RECOVERY SYSTEM
WEIGHT.....15,874 LB
COST..........

PRESSURE FED
RECOVERY SYSTEM
WEIGHT.....24,220 LB
COST..........

BACKU: #7

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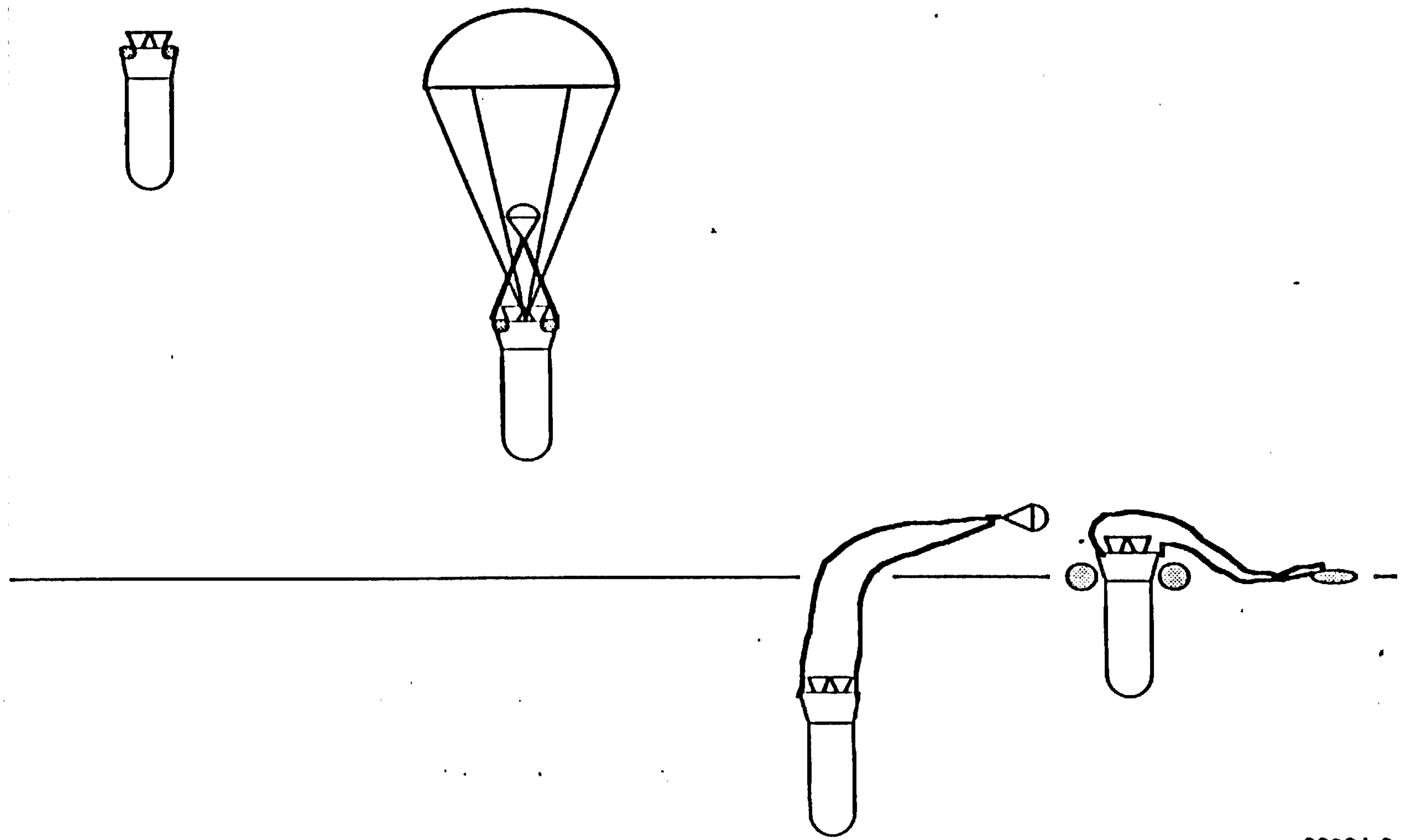
# SSME WATER PROTECTION

**LRB**



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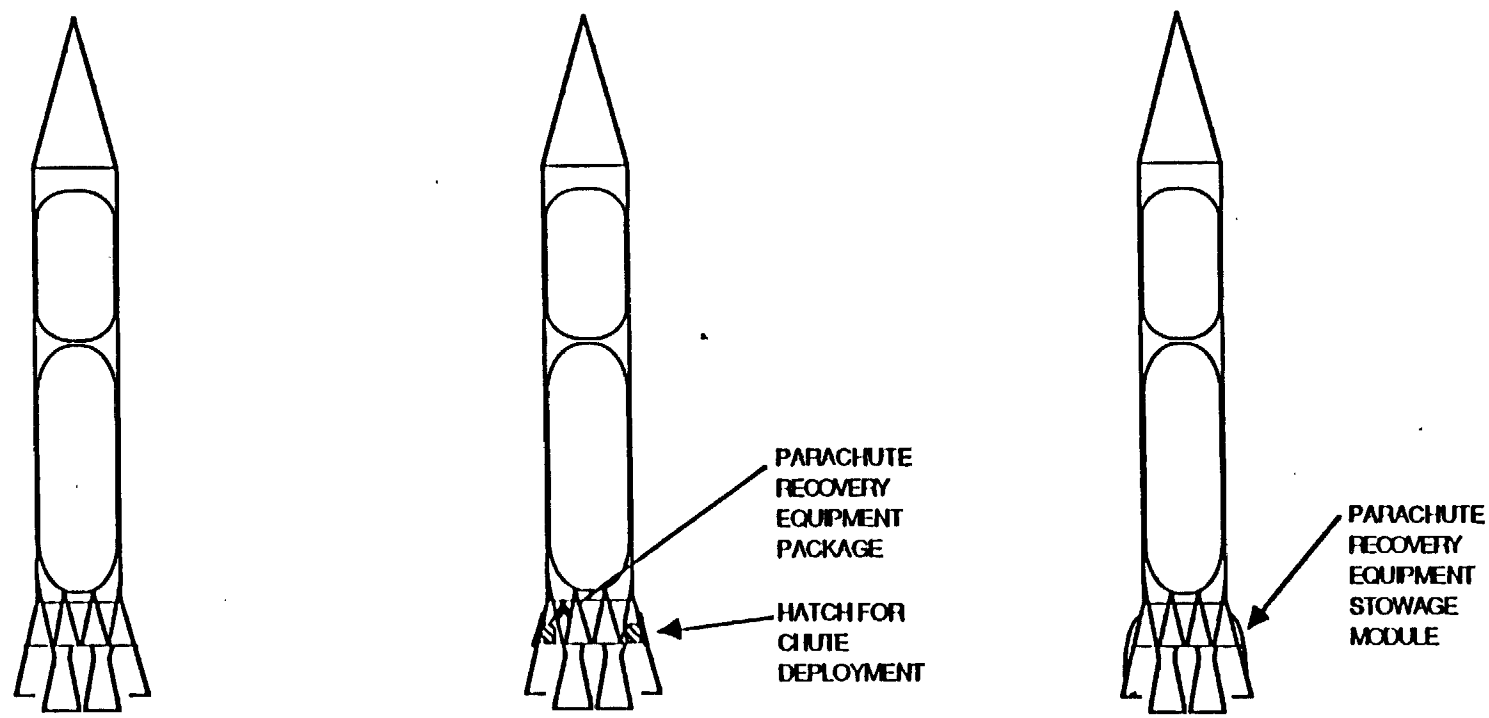
# PARACHUTE RECOVERY EQUIPMENT STOWAGE
# LRB WITH LO2/LH2 ENGINE




EXPENDABLE — INTERNAL STOWAGE — EXTERNAL STOWAGE

**INTERNAL STOWAGE**

MAX. WEIGHT DIFFERENTIAL CASE

| | |
|---|---|
| EXTENDED SKIRT AND HATCH | 800 lbs |
| PARACHUTE EQUIPMENT | 10150 lbs |
| P/A CLAMSHELL | 3800 lbs |
| TOTAL WEIGHT | 14750 lbs |

**EXTERNAL STOWAGE**

MIN. WEIGHT DIFFERENTIAL CASE

| | |
|---|---|
| PARACHUTE EQUIPMENT COVER | 300 lbs |
| PARACHUTE EQUIPMENT | 10150 lbs |
| P/A SOCK | 1400 lbs |
| TOTAL WEIGHT | 11850 lbs |

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# ROCKWELL SEA LANDING ASSESSMENT

LRB

* <u>PROPOSED 6 FPS - REQUIRES PARACHUTES AND RETROROCKET</u>

* LIMIT ENTRY IMPACT, STRUCTURAL LOADS AND PRESSURES
* CONSIDER ERRORS IN PARACHUTE +- 5FPS
* DESCENT VARIATIONS DUE TO HUMIDITY.
* RETROROCKET IGNITION TIME VARIATION +- 5 FT AT 100 FT/SEC

NOTE: SEAS GREATER THAN 8.5 FT WILL OVER STRESS THE PUMP FED LRB.

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# SURVIVABILITY of LRB TANKS

LRB

PUMP FED LRB

- SUBMERGED WATER LANDING WILL COLLAPSE TANK. WATER DEPTH OF 7 FEET PRODUCES 3 PSI
- 8.5 FOOT WAVES WILL EXCEED STRENGTH OF TANK

PRESSURE FED LRB

- TANK PRESSURE 100 PSI AFTER SEPARATION
- TANK GOOD FOR 10 G'S IN ROUGH SEA
- LANDING IMPACT AT SEA NOT A PROBLEM FOR TANK

# LRB RECOVERY CONCEPT SELECTION
# RIGID WING - TOTAL LRB ONLY

LRB

| CRITERIA | | EVALUATION |
|---|---|---|
| SAFETY | HYDROGEN | • Will require safe handling from pad-pond/lagoon.<br>• Purging of tank required at dock, prior to overland transport through KSC |
| | RP - 1 | • Remove RP-1 at dock before transporting through KSC |
| RELIABILITY | | • Proposed fiberglass wings, and enpennage proven contemporary private aircraft concept.Swing-out within current state-ot-the-art. |
| RECOVERY / REFURBISHMENT OPERATIONS COMPATIBILITY | | • Wings and enponnage will have to be removed for refurbishing the LRB.<br>• After reassembly may require functional test. |
| LRB / STS COMPATIBILITY | | • As wings will lay on outer LRB surface, will have STS stacking operations interfaces.<br>• Will have aerodynamic influences during ascent. |
| RISK | | • High development and operational risk.<br>• No simple way to flight-test; deployment through landing<br>• Too risky, parawing better winged option |

# LRB RECOVERY CONCEPT SELECTION PARAWING - PARTIAL AND TOTAL LRB

## LRB

| CRITERIA | | EVALUATION |
|---|---|---|
| SAFETY | HYDROGEN | • Will require safe handling from pad-pond/lagoon.<br>• Purging of tank required at dock, prior to overland transport through KSC |
| | RP -1 | • Remove RP-1 at dock before transporting through KSC |
| RELIABILITY | | • Analogous to contemporary air inflated parafoils.<br>• Deployment (mechanical with aero assistance) and operational reliability should be higher than parafoils and ram air stabilized wings. |
| RECOVERY / REFURBISHMENT OPERATIONS COMPATIBILITY | | • Packaged along length of LRB.<br>• Will have to be removed for LRB refurbishment.<br>• For P/A recovery, via 1/2 LRB, will be removed for refurbishment and assembly to new LRB. |
| LRB / STS COMPATIBILITY | | • No apparent STS stacking interference.<br>• Low x-axis profile offers little aerodynamic influence during ascent. |
| RISK | | • Low development and operational risk.<br>• Analogous to high glide parachutes. |

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# LRB RECOVERY CONCEPT SELECTION PARACHUTE - PARTIAL AND TOTAL LRB

LRB

| CRITERIA | | EVALUATION |
|---|---|---|
| SAFETY | HYDROGEN | • Will require safe handling from pad-pond / lagoon.<br>• Purging of tank required at dock, prior to overland transport through KSC |
| | RP-1 | • Remove RP-1 at dock before transporting through KSC |
| RELIABILITY | | • Proven concept for SRM recovery |
| RECOVERY / REFURBISHMENT OPERATIONS COMPATIBILITY | | • Similar to SRB, except for safing |
| LRB / STS COMPATIBILITY | | • Packing about boat-tail affords no interference with stacking |
| RISK | | • Same as for SRB |

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# WEIGHT SUMMARY PUMP FED LRB

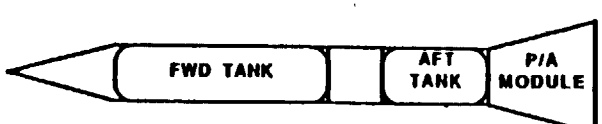
LRB

| RECOVERY MODE | BALLISTIC-DOWNRANGE | | | RTLS-TOW BACK | | | | | RTLS-TOSS BACK | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RECOVERY TYPE | PARACHUTE | | | PARAWING | | | | RIGID WING | PARAWING | | | RIGID WING |
| RECOVERABLE | 1/2 LRB (AFT TANK + P/A) | | | 1/2 LRB (AFT TANK + P/A) | | | LRB | LRB | LRB | LRB | 1/2 LRB | LRB |
| OPTIONS | ENGINE EXPOSED TO WATER | CLAM | SOCK | ENGINE EXPOSED TO WATER | CLAM | SOCK | ENGINE EXPOSED TO WATER | ENGINE EXPOSED TO WATER | STRAP ON SOLID MOTOR | RESTART | RESTART | RESTART |
| CONFIGURATION | | | | | | | | | | | | |
| 5A LOX / LH2 NEW PUMP FED | 1.03XWI 1.02XWp | N/A* | N/A* | 1.15XWI 1.04XWp | N/A* | N/A* | 1.19XWI 1.05XWp | 1.4XWI 1.06XWp | 1.84XWI 1.39XWp | 1.30XWI 1.16XWp | 1.24XWI 1.16XWp | 1.56XWI 1.2XWp |
| 5D LOX / RP-1 NEW PUMP FED | 1.02XWI 1.01XWp | N/A* | N/A* | 1.13XWI 1.02XWp | N/A* | N/A* | 1.16XWI 1.02XWp | 1.38XWI 1.05XWp | | | | |
| 5J LOX / LH2 SSME-35 | 1.02XWI 1.0XWp | 1.06XWI 1.01XWp | 1.03XWI 1.01XWp | 1.15XWI 1.01XWp | 1.17XWI 1.02XWp | 1.14XWI 1.01XWp | 1.15XWI 1.01XWp | 1.37XWI 1.07XWp | | | | |

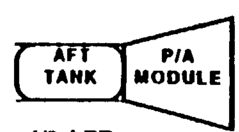
**OPTIONS:**

EXPOSED = NO WATER PROTECTION FOR ENGINE
CLAM = CLAM SHELL WATER PROTECTION FOR ENGINE
SOCK = WATER PROTECTION FOR ENGINE
STRAPON = SOLID ROCKET TO OBTAIN TOSS BACK VELOCITY
RESTART = USE MAIN ENGINE FOR TOSS BACK VELOCITY

WI = INERT WEIGHT
Wp = PROPELLANT WEIGHT
N/A* = WATER PROTECTION INCORPORATED INTO NEW ENGINE DESIGN




LRB




1/2 LRB

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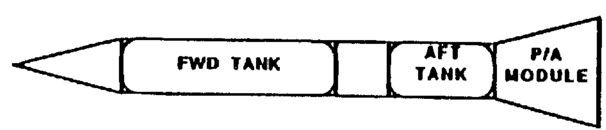
# WEIGHT SUMMARY PRESSURE FED LRB

LRB

| RECOVERY MODE | BALLISTIC | RTLS-TOW BACK | | RTLS-TOSS BACK | | |
|---|---|---|---|---|---|---|
| RECOVERY TYPE | PARACHUTE | PARAWING | RIGID WING | PARAWING | | RIGID WING |
| RECOVERABLE | LRB | LRB | LRB | LRB | LRB | LRB |
| OPTIONS / CONFIGURATION | ENGINE EXPOSED TO WATER | ENGINE EXPOSED TO WATER | ENGINE EXPOSED TO WATER | STRAP ON SOLID MOTOR | RESTART | RESTART |
| 1B LOX / RP-1 PRESSURE FED | 1.02 X Wi<br>1.04 X Wp | 1.16X Wi<br>1.03 X Wp | 1.38 X Wi<br>1.08 X Wp | BEST RECOVERY MODE IS BALLISTIC PARACHUTE | | |

OPTIONS:
EXPOSED - NO WATER PROTECTION FOR ENGINE
STRAPON - SOLID ROCKET TO OBTAIN TOSS BACK VELOCITY
RESTART - USE MAIN ENGINE FOR TOSS BACK VELOCITY

Wi - INERT WEIGHT
Wp - PROPELLANT WEIGHT




LRB

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# COST ESTIMATING
# GROUND RULES AND ASSUMPTIONS

**LRB**

| | LAND RECOVERY/DRY WATER RECOVERY(1) | | WATER RECOVERY (SEA WATER) | |
|---|---|---|---|---|
| | DESIGN LIFE | % OF T1 COST FOR REFURB | DESIGN LIFE | % OF T1 COST FOR REFURB |
| • ENGINES | | | | |
| SSME | 40 | 20% | 25 | 30% |
| NEW PUMP-FED | N/A | N/A | 25 | 25% (3) |
| NEW PRESSURE-FED | N/A | N/A | 25 | 20% |
| ACTUATORS | | | | |
| ELECTROMECHANICAL ACTUATORS | 25 | 10% | 25 | 15% |
| STRUCTURES | | | | |
| TANKS | N/A | N/A | 100 (2) | 15% |
| ADAPTERS | N/A | N/A | 100 | 15% |
| THRUST STRUCTURE | N/A | N/A | 100 | 15% |
| MAIN PROPELLANT SYSTEM | N/A | N/A | 100 | 15% |
| WINGS (PARA/RIGID) | N/A | N/A | 10/100 | 15% |

- RECOVERY RELIABILITY 97%
- CONSTANT FY 87 DOLLARS
- NINE (9) LAUNCHES PER YEAR
- LRB OPERATIONS INCLUDE ASSEMBLY, PROCESSING AND CHECKOUT FOR LAUNCH
- EXCLUSIONS:
  - PROPELLANT AND RECOVERY OPERATIONS
  - ASCENT RELIABILITY
  - AVIONICS AND SOFTWARE
  - CONTRACTOR FEE; RESERVE; GOVT SUPPORT

(1) DRY WATER RECOVERY USING THE SOCK OR CLAMSHELL
(2) EXCEPTION: LH2 TANK DESIGN LIFE LIMITED TO 15 FLIGHTS DUE TO CRYO DETERIORATION
(3) IF NEW ENGINE HAS PROTECTED TURBOPUMP, THE REFURB WOULD BE SIGNIFICANTLY REDUCED

# COST SUMMARY PUMP FED LRB

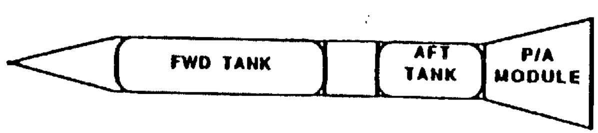
| RECOVERY MODE | BALLISTIC-DOWNRANGE | | | RTLS-TOW BACK | | | | | RTLS-TOSS BACK | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RECOVERY TYPE | PARACHUTE | | | PARAWING | | | | RIGID WING | PARAWING | | | RIGID WING |
| RECOVERABLE | 1/2 LRB (AFT TANK + P/A) | | | 1/2 LRB (AFT TANK + P/A) | | | LRB | LRB | LRB | LRB | 1/2 LRB | LRB |
| OPTIONS | ENGINE EXPOSED TO WATER | CLAM | SOCK | ENGINE EXPOSED TO WATER | CLAM | SOCK | ENGINE EXPOSED TO WATER | ENGINE EXPOSED TO WATER | STRAP ON SOLID MOTOR | RESTART | RESTART | RESTART |
| CONFIGURATION | | | | | | | | | | | | |
| 5A LOX / LH2 NEW PUMP FED | 0.95Ex | N/A* | N/A* | | N/A* | N/A* | | | | | | |
| 5D LOX / RP-1 NEW PUMP FED | 1.09Ex / 1.03Ex | N/A* | N/A* | | N/A* | N/A* | 1.15Ex | 1.31Ex | | | | |
| 5J LOX / LH2 SSME-35 | | | 0.74Ex | | | | | | | | | |

**OPTIONS:**

EXPOSED = NO WATER PROTECTION FOR ENGINE
CLAM = CLAM SHELL WATER PROTECTION FOR ENGINE
SOCK = WATER PROTECTION FOR ENGINE
STRAPON = SOLID ROCKET TO OBTAIN TOSS BACK VELOCITY
RESTART = USE MAIN ENGINE FOR TOSS BACK VELOCITY

Ex = EXPENDABLE
N/A* = WATER PROTECTION INCORPORATED INTO NEW ENGINE

9 FLIGHTS/YEAR
15 FLIGHTS/YEAR



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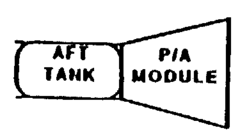

1/2 LRB

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# COST SUMMARY PRESSURE FED LRB

LRB

| RECOVERY MODE | BALLISTIC | RTLS-TOW BACK | | RTLS-TOSS BACK | | |
|---|---|---|---|---|---|---|
| RECOVERY TYPE | PARACHUTE | PARAWING | RIGID WING | PARAWING | | RIGID WING |
| RECOVERABLE | LRB | LRB | LRB | LRB | LRB | LRB |
| OPTIONS / CONFIGURATION | ENGINE EXPOSED TO WATER | ENGINE EXPOSED TO WATER | ENGINE EXPOSED TO WATER | STRAP ON SOLID MOTOR | RESTART | RESTART |
| 1B LOX / RP-1 PRESSURE FED | >1.10Ex | | | BEST RECOVERY MODE IS BALLISTIC PARACHUTE | | |

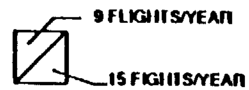
OPTIONS:

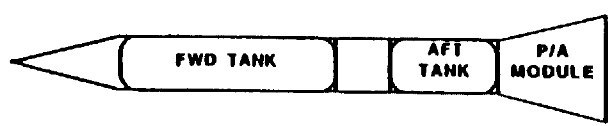
EXPOSED = NO WATER PROTECTION FOR ENGINE

STRAPON = SOLID ROCKET TO OBTAIN TOSS BACK VELOCITY

RESTART = USE MAIN ENGINE FOR TOSS BACK VELOCITY

Ex = EXPENDABLE




LRB

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# LRB RECOVERY DOWNSELECT MEETING

LRB

CONCLUSIONS:

- RRR of pump-fed P/A and pressure-fed LRB marginally cost effective
  - Sensitive to cost assumptions and mission rates
- Downrange parachute best recovery option
  - Lowest risk, least KSC impact

RECOMMENDATIONS:

- Continue RRR on downrange parachute options
  - Emphasis on (1) new engine LOX/LH2 & RP-1; (2) pressure-fed LRB
  - Evaluate
    - •operations/facilities impact
    - •LRB phase-in with SRB
    - •refurb phase-in to LRB production/use
    - •total costs with mission rate sensitivities
    - •other

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UPDATE ON T.S. 1.13 RECOVERY SYSTEMS

At the midterm review we recommended that LRBs be expended based on cost estimates which at that time showed:

An additional development expenditure of over $1B should just about pay for itself in 100 flights (LOX/RP vehicle).

Investigation of the cost effectiveness of recovery and reuse includes: a) upsized vehicle and engine to handle the added weight of recovery systems, b) an allowance of approximately 10% for LRBs lost in the recovery attempt, and c) estimates of 15% to 50% refurbishment costs.

Our data continues to show that reusability approximately breaks even for LRB flight ratres up to 15/year. For other vehicles at higher flight rates, recovery and reuse may be cost effective.

TRADE STUDY 1.15
FINAL ERB
**FEBRUARY 11, 1988**

# 1.15 FACILITY OPTIMIZATION


STUDY LEADER: JOHN WASHBURN

SYSTEMS ENGINEER: LOU PEÑA

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# 1.15 FACILITY OPTIMIZATION
# Planning Sheet 1

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## OBJECTIVE:

- DETERMINE BEST LAUNCH/MCS CONCEPTS, FACILITIES AND GSE TO PROCESS AND LAUNCH THE LRB, WHILE MINIMIZING INTERFACE IMPACTS WITH THE STS.

## GROUNDRULES/ASSUMPTIONS/GUIDELINES:

- ON-LINE PROCESSING WILL MINIMIZE CHANGES TO CURRENT STS PROCESSING
- ON-LINE PROCESSING WILL COMPLY WITH STS REQUIREMENTS EXCEPT AS IDENTIFIED AND JUSTIFIED
- PROCESSING WILL BE OPTIMIZED TO MINIMIZE RECURRING COSTS
- ASSUME NEW LAUNCH PROCESSING SYSTEM

# 1.15 FACILITY OPTIMIZATION
## Planning Sheet 2

### REQUIREMENTS:

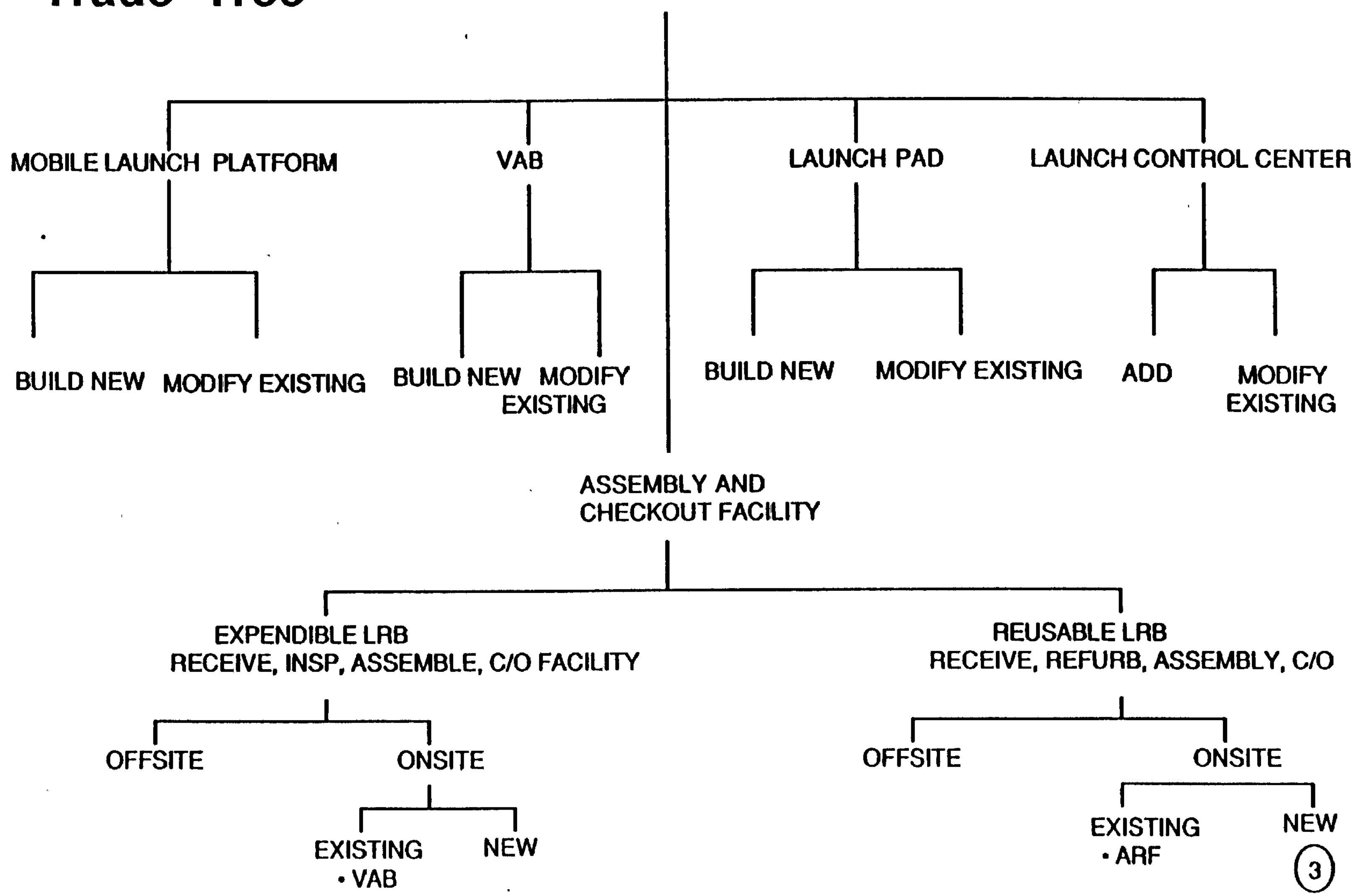
- MINIMIZE MODIFICATION TO EXISTING STS FACILITIES/GSE
  - FLAME TRENCH
  - PROPELLANTS
  - ICING
  - VAB
  - MLP
  - LPS/MCS
  - GROUND ACCESS
- SUPPORT 14 FLIGHTS PER YEAR
- MODIFICATIONS NOT TO INTERFERE WITH ON-GOING OPERATIONS
- SAFETY (NHB 5300.4, NSTS 07700)

### CONSTRAINTS:

- ON-LINE PROCESSING WILL BE SIMILAR TO EXISTING STS PROCESSING

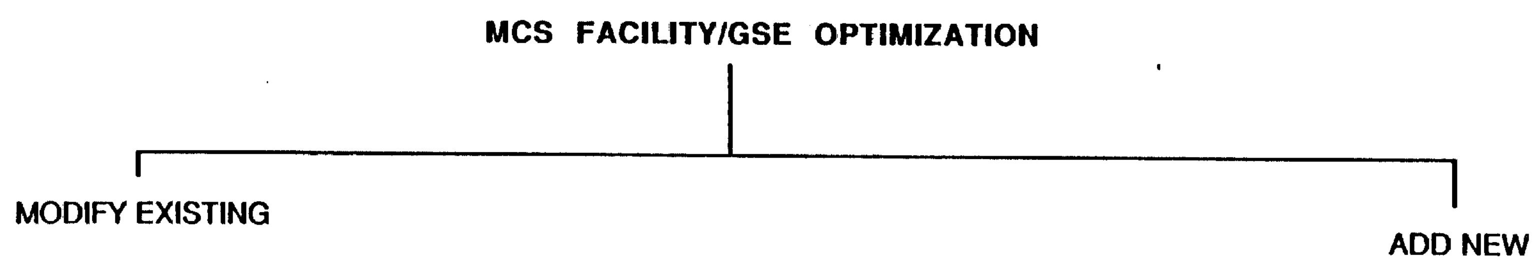
# 1.15 FACILITY OPTIMIZATION
## Planning Sheet 4

## Trade Tree



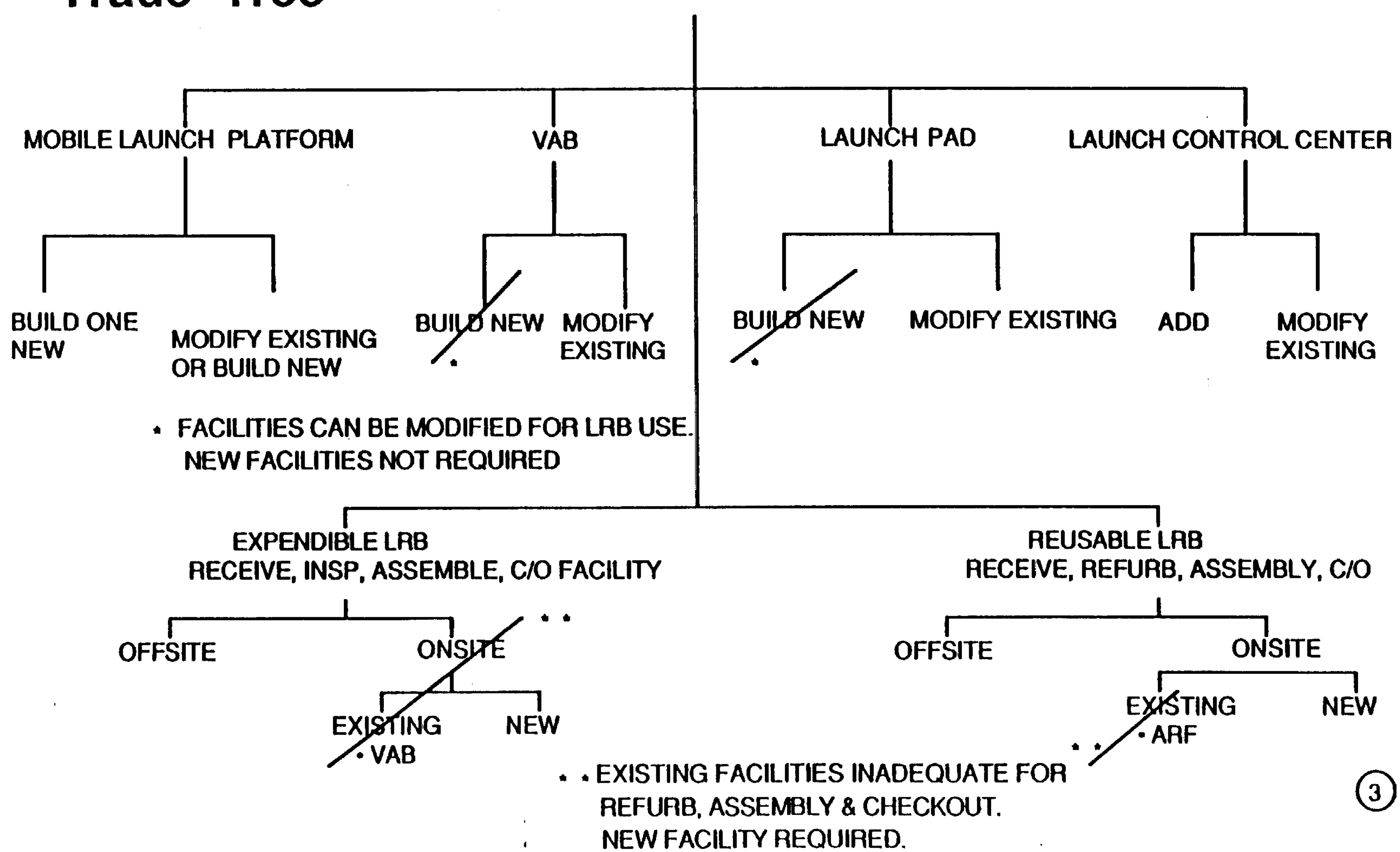
# 1.15 FACILITY OPTIMIZATION
## Planning Sheet 4

## Trade Tree



# 1.15 FACILITY OPTIMIZATION
## Planning Sheet 4

## Trade Tree



# 1.15 FACILITY OPTIMIZATION
# Planning Sheet 5

## INPUTS:

- 1.1 CONFIGURATION
- PROPELLANT SELECTION (1.5 & 1.6)
- FLAME TRENCH MODS (1.5 & 1.6)
- 1.4 DEGREE OF RECOVERY/REUSABILITY

## OUTPUTS:

- OPTIMIZED OFF-LINE GROUND OPERATIONS/FACILITIES
- MODIFICATION COST & SCHEDULES
- RECURRING COST ESTIMATES

## OTHER TRADES AFFECTED:

- 1.1 LENGTH/DIAMETER OPTIMIZATION
- 1.2 NUMBER OF ENGINES
- 1.3 ABORT MODE OPTIMIZATION, 1.11 IGNITION SEQUENCE
- 1.5 & 1.6 PROPELLANT SELECTION
- 2.4 DEGREE OF AUTOMATION
- 2.6 PRODUCTION SITE OPTIONS
- 2.10 RECOVERY SITE/MODE
- 1.4 RECOVERY/REUSABILITY
- EVOLUTION/GROWTH

4

# 1.15 FACILITIES OPTIMIZATION
## Summary of Results - MCS

**CONCLUSIONS:**

- MCS WILL BE DRIVEN BY JSC FLIGHT OPS REQUIREMENTS

**RECOMMENDATIONS:**

# 1.15 FACILITIES OPTIMIZATION
## Summary of Results - Reuseable

**CONCLUSIONS:**

- EXISTING ON-SITE FACILITIES NOT ADEQUATE FOR REFURB, ASSY & C/O
  NO GROWTH CAPABILITY
- OFF-SITE OFFERS GREATEST REFURB, ASSEMBLY & C/O EFFICIENCY, GROWTH POTENTIAL

**RECOMMENDATIONS:**

- FOR REUSEABLE CONCEPTS, EXPLORE KSC AREA FACILITY

# 1.15 FACILITIES OPTIMIZATION
## Summary of Results - Expendable

279

**CONCLUSIONS:**

- EXISTING ON-SITE FACILITES NOT ADEQUATE, NO GROWTH
- OFF-SITE OFFERS GREATEST ASSEMBLY & C/O EFFICIENCY

**RECOMMENDATIONS:**

- BASELINE OFF-SITE ASSEMBLY & CHECKOUT (SHIP & SHOOT)
- SELECT OFF-SITE LOCATION IN CONJUNCTION WITH MANUFACTURING SITE SELECTION

# 1.15 FACILITIES OPTIMIZATION
## Summary of Results - LC-39

### CONCLUSIONS:

- IDENTIFIED LC-39 (VAB,LCC,PAD) MODIFICATIONS FOR EACH LRB CONCEPT
- MODS ARE MANAGEABLE - MIN INTERFERENCE TO ON-GOING STS OPERATIONS
  - SUPPORT 14 STS FLIGHTS/YEAR
  - LSOC AGREES WITH ASSESSMENT

### RECOMMENDATIONS:

- START VAB MODIFICATIONS EARLY - 1992

# FACILITY OPTIMIZATION

The top row indicates the on-line KSC facilities and launch support equipment that we examined to determine their adequacy for an LRB and the options, either to modify existing or build new. Because of the high utilization of the Mobile Launch Platforms (MLP) to support on-going SRB operations, it will be necessary to build at least one new MLP to support the initial LRB operations. The need to build additional new or modify the existing MLPs to the LRB configuration can be determined later. The existing VAB highbays 1 & 3 used to integrate the STS flight elements can be modified to accommodate the LRB. Because of the increased diameter of the LRBs versus the SRBs, the existing platforms must be modified to fit the LRBs and also to provide clearance for the STS with LRBs to clear the platforms as the STS leaves the VAB for the launch pad. It was also determined that the existing launch pads can be modified to handle the LRB, precluding having to build an entirely new one. The principal modification will be the addition of propellant storage andtransfer systems for propellants other than LO2 and LH2. For these 2 cryogenic propellants, the LRBs can be serviced by teeing off the existing ET propellant systems on the MLP. The question of either adding a Launch Control Center or modifying the existing one depends to a great extent on the projected usage of the existing 4 LCCs. Current projections show almost full utilization of the LCCs; however, software modification and development may be poosible to schedule into the LCCs during on-going operations.

For both the expendable and reuseable versions of the LRB, we examined the possiblity of using existing on-site facilities for LRB receipt, inspection,refurbishment for recoveralbe, final assembly and checkout. The existing facilities were inadequate for this task, primarily because of the difficulty in integrating into on-going operations and also because of limited potential for increasing the LRB processing activity sufficiently to handle the STS plus any LRB growth options.

# ASSEMBLY & CHECKOUT - KSC FACILITIES

This matrix summarizes the advantages and disadvantages of various options for LRB final assembly and checkout facilities at KSC. The selected option is to build a new facility that can be built to optimize the efficiency of LRB final assembly and checkout and refurbishment operations for the reuseable versions.

# 1:15 FACILITY OPTIMIZATION

## ASSEMBLY & CHECKOUT - KSC FACILITIES

| LOCATION | REQMTS | ADVANTAGES | DISADVANTAGES |
|---|---|---|---|
| On Site Assembly & Checkout | • Access to VAB<br>• LPS C/O | • Min LRB xport<br>• Rapid Response to sched changes | • Generally not KSC work |
| Existing Facilities | | • Min facility costs | • Integrate mods & LRB ops with ongoing ops |
| • ARF | | • Horizontal - most efficient | • Transition with SRB ops<br>• Limited growth |
| • RPSF | | • Horizontal - 4 LRBs | • Transition not compatable |
| • VAB Low Bays | | • Horizontal | • Not large enough |
| • VAB High Bays 2 & 4 | | | • Vertical - least efficient<br>• 75 days/year lost time due to SRB/ET stacking<br>• Limited growth |
| New Facility | | • Optimize efficiency | • Const of Fac cost/sched<br>• ARF RPSF utilization |

# 1.15 FACILITY OPTIMIZATION

## KSC LC - 39 FACILITY MODIFICATIONS

| | ~~LO2/LH2 SSME-35 5J~~ | ~~LO2/RP-1 F-1 5K~~ | LO2/LH2 New Pump 5A | LO2/RP-1 New Pump 5D | LO2/RP-1 New Press 1B |
|---|---|---|---|---|---|
| **VAB** | | | | | |
| Platforms | ~~New/Mod~~ | ~~New/Mod~~ | New/Mod | New/Mod | New/Mod |
| Doors | ~~---~~ | | --- | | --- |
| **MLP** | | | | | |
| Propellant Service | ~~Tee~~ | ~~Tee/New~~ | Tee | Tee/New | Tee/New |
| Vent Masts | ~~X~~ | ~~LO2~~ | X | LO2 | LO2 |
| **Launch Pad** | | | | | |
| ET GOX Vent Arm | ~~New/Mod~~ | ~~New/Mod~~ | New/Mod | --- | New |
| ET GH2 Vent Arm | ~~New/Mod~~ | | New/Mod | --- | --- |
| Prop Store & Xfer | ~~---~~ | ~~RP-1~~ | LH2? | RP-1 | RP-1 |
| Booster Process Fac | | | | | |

# KSC LC - 39 FACILITY IMODIFICATIONS

The LC - 39 facility modifications required to accommodate the three selected LRB configurations are shown by major facility, VAB,MLP, and launch pad. The platforms in the VAB that enclose the STS vehicle and provide access to all the STS elements must be modified to accommodate the larger diameter of the LRBs compared to the SRBs. The platform above the SRB must also be changed becasue of the longer LRBs. Becasue the three MLPs will be fully used for launching SRB Shuttles, at least one new MLP must be built, with a decision made later as to whether to build additional new MLPs or modify the existing ones. The MLP must have propelaant servicing equipment installed: piping, valves, control skids and computer interface hardware to permit tanking control of the propellant system. Both LO2 and LH2 will be teed off the existing External Tank propellant systems whereas an entirely new system would have to be installed for the RP-1. Vent accommodations must be proveded for the LH2 to insure the explosive gaseous hydrogen is removed from the vicinity of the Shuttle. LO2 vent may be required to prevent ice formation with the potential of ice damage to the orbiter tiles at lift-off. Because LRB configurations 5A & 1B are so much longer than the SRBs, they would protrude into the ET GOX vent arm; therefore, the GOX vent arm must be modified to prevent the physical interference. The bigger diamter (15+ feet) of LRB configuration 5A would also require a mod to the LH2 vent arm to prevent physical interference. The current LH2 storage capacity at the launch pads is marginal for servicing the ET plus both LRBs. The LH2 storage capacity may have to be increased; however, we would still plan to use the existing transfer system which has sufficient transfer capactiy for all three LH2 tanks.

# 1.15 FACILITY OPTIMIZATION

## ASSEMBLY & CHECKOUT - OFF SITE

| LOCATION | REQS | ADVANTAGES | DISADVANTAGES |
|---|---|---|---|
| Off Site Assembly & Checkout | • Inland water-way access | • Min impact to KSC<br>• Employ Impact | • ARF - RPSF utilization after LRB transition |
| Local to KSC | • New contruct | • Optimize efficiency<br>• Rapid response to sched changes | • Environmental hurdles |
| Distant off site | • Temp storage & contingency maint at KSC (VAB HB 2&4) | • Michoud<br>- exist gov facility<br>- KSC & NSTL access<br>- co-locate manufac | • Transporttation costs<br>- ~$100K/launch<br>- $7M/barge |

# ASSEMBLY & CHECKOUT - OFF SITE

The major advantage of locating a fianl assembly and checkoutfacilyt off-site is that there would be minimum impact to KSC during the construction of such a facility,f pflus the assembly and checkout operations themselves would not interfere with the KSC work. Local assembly and checkout has the advantages of rapid schedule response; however, if planned for the inland waterway, surmounting the environmental concerns could be a major hurdle. If the LRB were assembled and checked out at a distant location, it would require a temporary storage and contingency maintenance area at KSC, which the VAB highbays 2 & 4 would be satisfactory for these functions. Distant assembly and checkout would also add some transportation costs to the program also; however, this should not be a determining factor. The final location for the final assembly and checkout facility will be selected during the manufacturing study to be conducted later in the LRB program.

# KSC FACILITY IMPACTS

Another major selection criteria was concept/propellant compatibility with the KSC facilities. In conjunction with our subcontractor, PRC, we listed significant changes which would be required. In the VAB, all concepts are larger in diameter and length than the SRB's, so modifications are required to the work platforms. Since storables are the smallest LRB, platform changes are the least. No concepts would require changes to the VAB doors.

On the MLP all types of propellants necessitate new propellant service lines, control skids, and service masts to fill and drain the LRB's. For LOX and $LH_2$ these services can tee off the lines to the orbiter. Venting the east LRB requires a new vent mast, either on the MLP, or directly on the concrete deck with lines to the disposal system. RP - 1 and probably $C_3H_8$ can be vented to atmosphere. Since storable propellants can be loaded before the final countdown, a temporary vent system would be sufficient. All propellant types require new propellant storage and transfer except LOX and perhaps $LH_2$ (Cx 39 capacity is marginal)

ROM cost estimates, made by PRC, varied from about 21 to 32 million dollars. $LH_2$ and $CH_4$ systems were the highest due to their requirement for expensive vacuum jacketed systems. These costs were not regarded as significant drivers in concept selection.

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# KSC FACILITIES / IMPACTS

LRB

| | LOX/LH2 | LOX/RP-1 | NTO/MMH | NTO/MMH |
|---|---|---|---|---|
| **VAB** | | | | |
| PLATFORMS | NEW | NEW | MOD | NEW |
| DOORS | ------ | ------ | ------ | ------ |
| **MLP** | | | | |
| PROPELLANT SERVICE | TEE OFF ORBITER SYS& NEW CONTROL SKIDS | LOX: TEE,FUEL:NEW & NEW CONTROL SKIDS | ALL NEW SYSTEM | LOX:TEE, FUEL:NEW |
| VENT MASTS (EAST) | NEW LOX AND LH2 | NEW LOX | TEMPORARY | NEW LOX AND CH4 |
| **LAUNCH** | | | | |
| ET GOX VENT ARM | MOD | ------ | ------- | ------- |
| ET GH2 VENT ARM | MOD | MAY MOD | MAY MOD | MOD |
| PROPEL. STORAGE & TRANSFER | EXISTING( MAY ADD LH2 STORAGE) | NEW SATURN TYPE FUEL | ALL NEW | NEW FUEL |
| DISPOSAL | ENLARGE LH2 LINES ADD LH2&GOX ARMS | GOX VENT ARM | SCRUBBRS & LARGER MOBILE CLEAN EQ. | NEW CH4 AND GOX VENT ARMS |
| COST ESTIMATES M$ | 31 | 22-24 | 22 | 21-32 |

NOT A SIGNIFICANT DRIVER IN CONCEPT SELECTION

LIQUID ROCKET BOOSTER
TRADE STUDY ERB
February 26, 1988

TRADE STUDY 1.16
MIDTERM ERB

# SEPARATION SYSTEM SELECTION TRADE STUDY


STUDY LEADER: PAUL R. BRENNAN

SYSTEMS ENGINEER: LOU PENA


C-4


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# 1.16 SEPARATION SYSTEM SELECTION TRADE STUDY
## Planning Sheet 1

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**OBJECTIVE:** SELECTION OF THE MOST APPROPRIATE LRB SEPARATION SYSTEM. (THIS SYSTEM INCLUDES ELEMENTS TO INITIATE AND CONTROLTHE SEPARATION SEQUENCE, RELEASE THE BOOSTERS, AND PRODUCE THE IMPULSIVE FORCE NECESSARY FOR SAFE TRANSLATION AWAY FROM THE ORBITER AND ET. )

**GROUNDRULES/ASSUMPTIONS/GUIDELINES:**

GROUNDRULES:

- MAINTAIN CURRENT MOUNTING POINTS ON THE ET
- MAINTAIN CURRENT HARDWARE CONNECTIONS FOR RANGE SAFETY, DATA TRANSMISSION, AND POWER SUPPLY
- EXAMINE SEPARATION FOR CONTINGENCY ABORTS
- PROVIDE FOR FAIL-SAFE CAPABILITY

# 1.16 SEPARATION SYSTEM SELECTION TRADE STUDY
## Planning Sheet 1

**GROUNDRULES/ASSUMPTIONS/GUIDELINES (CON'T):**

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ASSUMPTIONS:

- LRB THRUST TERMINATED ($\leq$ 60,000 LBf) PRIOR TO SEPARATION
- SEPARATION SYSTEM PROVIDES NORMAL AND LATERAL ACCELERATION; RELATIVE AXIAL ACCELERATION ACHIEVED BY THE THRUST FROM THE SSME's

GUIDELINES:

- MINIMIZE MODIFICATIONS TO ETR FACILITES AND LAUNCH PROCESSING SCHEDULE
- AVIOD DESIGNS WHICH REQUIRE EXTENSIVE VERIFICATION TESTING
- CONSIDER 95% WINDS AND SYSTEM DISPERSIONS

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# 1.16 SEPARATION SYSTEM SELECTION TRADE STUDY
# Planning Sheet 2

## REQUIREMENTS:

| NUMBER | REQUIREMENT STATEMENT | SOURCE |
|---|---|---|
| 055 | CONTINGNECY ABORTS (MODIFIED)<br>Contingency abort failures include: (a) Loss of thrust from 2 or 3 SSME (b) SSME TVC failures (c) *LRB* TVC failures (d) Premature Orbiter separation (e) Failure to separate *LRBs* from Orbiter/ET. The following criteria shall apply for contingency aborts: (a) Contingency aborts will not be used to determine hardware design criteria (b) The Orbiters's and SSME usable lifetime may be degraded (c) Software and hardware impact may be allowed where feasible and cost effective, with specific approval. | NSTS 07700 X Para 3.2.1.5.2 |
| 008 | ENGINE-OUT PERFORMANCE<br>Safe abort must be possible with engine out on the Orbiter and/or one LRB. | HEALD |
| 028 | LRB SEPARATION SUBSYSTEM/ORBITER INTERFACE (MODIFIED)<br>The separaton subsystem shall include: a) The capacity to accept and respond to separation commands originating in the orbiter, (b) a release system, and (c) a system to translate the the*LRBs* away from the Oribter/ET. All sequencing commands shall come from the Orbiter. The release hardware and devices providing translation away from the Orbiter shall be the responsibility of the *LRBs*. Hardwire commands from the Orbiter to the *LRB* shall initiate the separation sequence. | SRB END ITEM SPECIFICATION Para 3.2.1.3 |

# 1.16 SEPARATION SYSTEM SELECTION TRADE STUDY
## Planning Sheet 2

### REQUIREMENTS (CON'T):

| NUMBER | REQUIREMENT STATEMENT | SOURCE |
|---|---|---|
| 023 | SEPARATION DAMAGE (MODIFIED)<br>The *LRB* separation subsystem shall provide for separation of the *LRBs* from the ET without damage to or recontact with the ET or Orbiter during or after separation. Damage to the *LRB/* ET connectors on the aft upper struts at the *LRB/* ET interface during LRB separation after ATVC power is deadfaced is acceptable. Particulates or damaging gases emited during booster separation shall not impinge on the Orbiter. The *LRB* separation subsystem shall not release any debris which could damage any Orbiter/ET system or subsystem. | NSTS 07700 X<br>Para<br>3.2.1.1.9 |
| 035 | SEPARATION SIGNAL INTERLOCK (MODIFIED)<br>The *LRB* separation subsystem shall incorporate signal interlocks to prevent *LRB* release and translation due to stray signals. The separation subsystem shall not release any debris which could cause damage to any Orbiter /ET system or subsystem during separation under conditions specified in design *LRB* staging conditions. | NSTS 07700 X<br>Para<br>3.2.1.1.9.1 |
| 029 | ORDNANCE CONTROL<br>All ordinace circuits shall utilize Pyro Initiators controllers per Rockwell International Space Division specification MC450-0018 and shall meet the requirement of pyrotechnic Specification JSC-08060 and AFETRM 127-1. | SRB END ITEM<br>SPECIFICATION<br>Para 3.2.1.5.5 |

# 1.16 SEPARATION SYSTEM SELECTION TRADE STUDY
## Planning Sheet 2

### ASSUMED REQUIREMENTS:

| NUMBER | REQUIREMENT STATEMENT | SOURCE |
|---|---|---|
| 036 | SEPARATION BODY RATE LIMITS (MODIFIED)<br>*LRB* separation shall automatically be inhibited if vehicle body rates and dynamic pressure exceed those values for which the separation system has the capability to perform a separation without causing damge to or recontact of Shuttle elements, with the exception of damage to the aft *LRB*/ ET electrical connectors after ATVC power is deadfaced. The crew shall be provided the capability to manually override these body rate dynamic pressure inhibits. | NSTS 07700 X<br>Para<br>3.2.1.1.9.1 |
| 037 | DESIGN *LRB* STAGING CONDITIONS (MODIFIED)<br>The *LRB* separation subsystem shall be designed to provide a safe separation for staging conditions which compose any combinations of values, within the separation limits, of these parameters:<br>a) Roll rate between plus or minus 5 degrees/sec<br>b) Pitch rate between plus or minus 2 degrees/sec<br>c) Yaw rate between plus or minus 2 degrees/sec<br>d) Dynamic pressure less than or equal to (TBD) psf<br>e) Pitch and sideslip angles plus or minus 15 degrees | NSTS 07700 X<br>Para<br>3.2.1.1.9.1 |
| 034 | SEPARATION TORQUE (MODIFIED)<br>Any component disconnect or breakwire at release shall not induce an impulse torque in excess of (TBD) ft-lb-sec about the *LRB* center of gravity at separation. | NSTS 07700 X<br>Para<br>3.2.1.1.9.1 |

2B

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# TRADE STUDY 1.16 - SEPARATION SYSTEM SELECTION
## Derived Requirements

| NUMBER | REQUIREMENT STATEMENT | CATEGORY | SOURCE |
|---|---|---|---|
| 075 | The LRBs shall use Solid Rocket Motors For Separation | Vehicle | Trade 1.16 |

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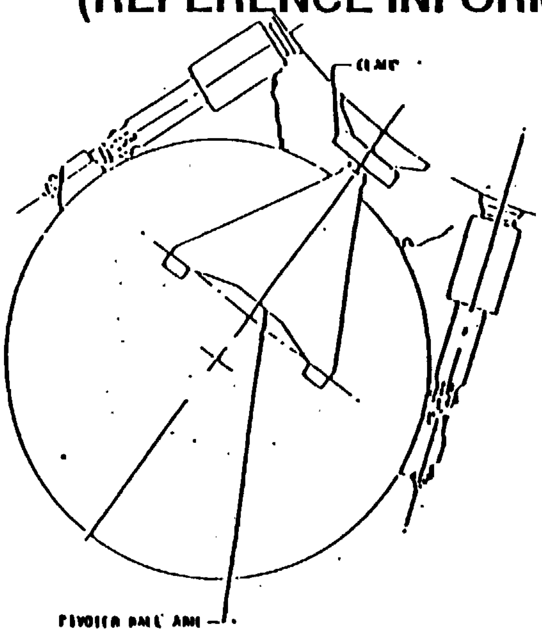
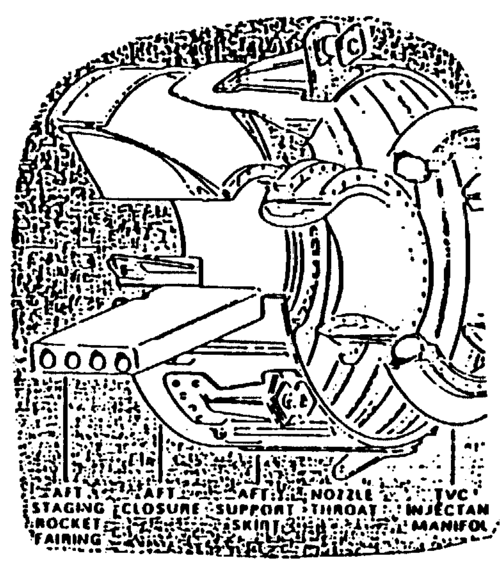
# 1.16 SEPARATION SYSTEM SELECTION TRADE STUDY (REFERENCE INFORMATION)



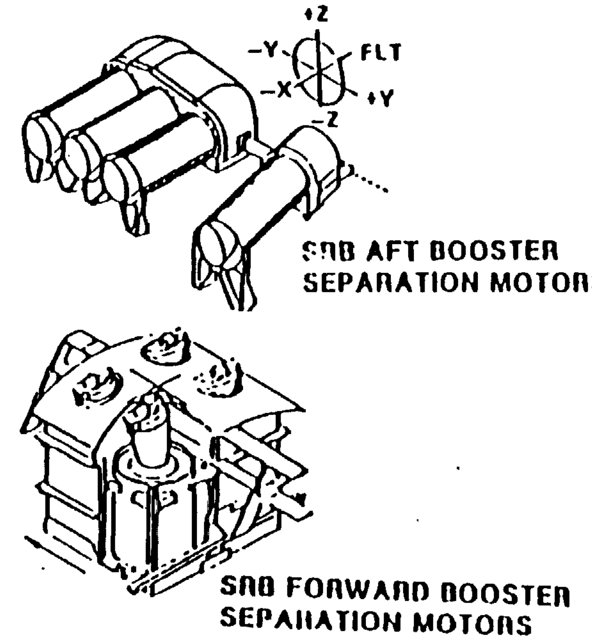
DELTA

- SRM BURNOUT
  WT = 2,360 lbs
- SEP SYSTEM WT =
- TYPE = PNEUMATIC THRUSTER
- TOTAL
  IMPULSE =



TITAN

- SRM BURNOUT
  WT = 89,910 LBS
- SEP SYSTEM WT = 1,238 lbs
- TYPE = STAGGING ROCKETS
- TOTAL VAC
  IMPULSE = 113,600 LB-SEC
  (8 MOTORS)




SHUTTLE

- SRB BURNOUT
  WT = 192,118 LBS
- SEP SYSTEM WT = 1,343 lbs
- TYPE = BSMs
- TOTAL VAC
  IMPULSE = 118,080 LB-SEC
  (8 MOTORS)

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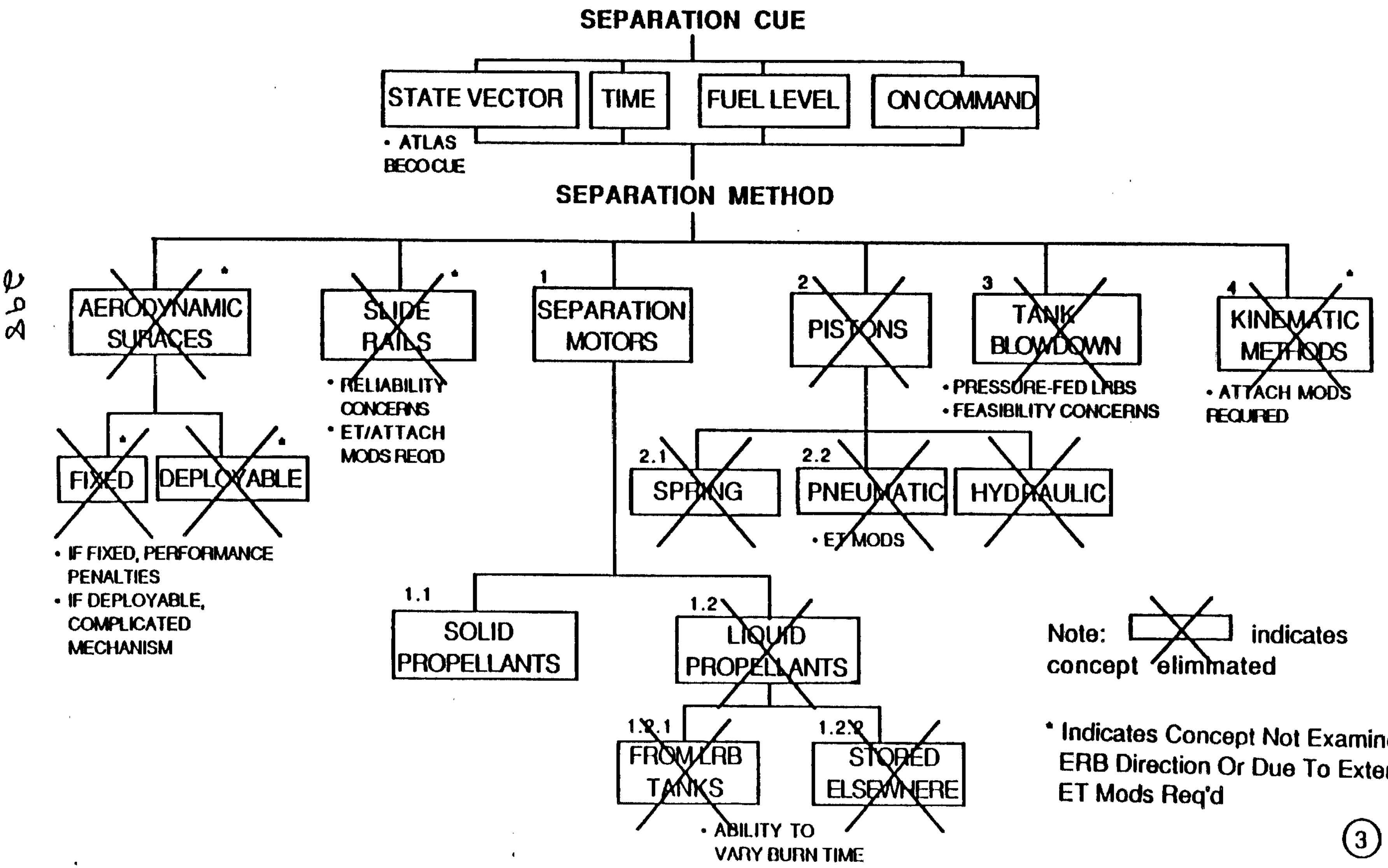
GENERAL DYNAMICS
Space Systems Division

# 1.16 SEPARATION SYSTEM SELECTION
## Planning Sheet 4
## Trade Tree




* Indicates Concept Not Examined Per ERB Direction Or Due To Extensive ET Mods Req'd

(3)

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# 1.16 SEPARATION SYSTEM SELECTION TRADE STUDY
## Planning Sheet 5

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**INPUTS:**

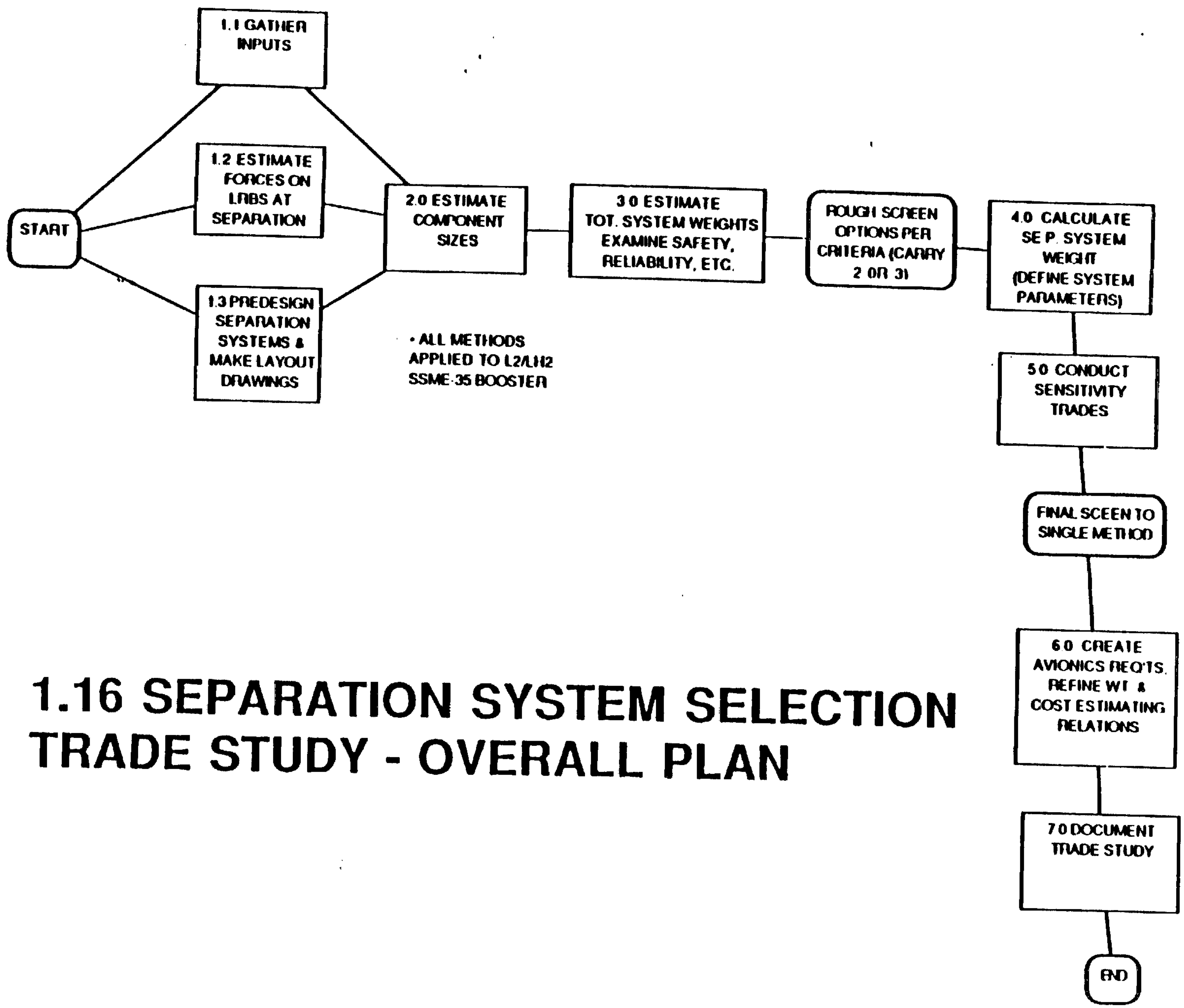
- CONTINGENCY ABORT STAGING CONDITIONS (RESULTS FROM ABORT MODE OPTIMIZATION TRADE STUDY 1. 3)
- BOOSTER MASS PROPERTIES & GEOMETRIC DEFINITION
- TRAJECTORY SIMULATION AND PROPULSION DATA
- BOOSTER AERODYNAMIC CHARACTERISTICS

**OUTPUTS:**

- SCALING RELATIONSHIPS (COST & WEIGHT) FOR SEPARATION SYSTEM
- PRELIMINARY SEPARATION SYSTEM DEFINITION AND SEQUENCE OF EVENTS
- PRELIMINARY SEPARATION AVIONICS REQUIREMENTS

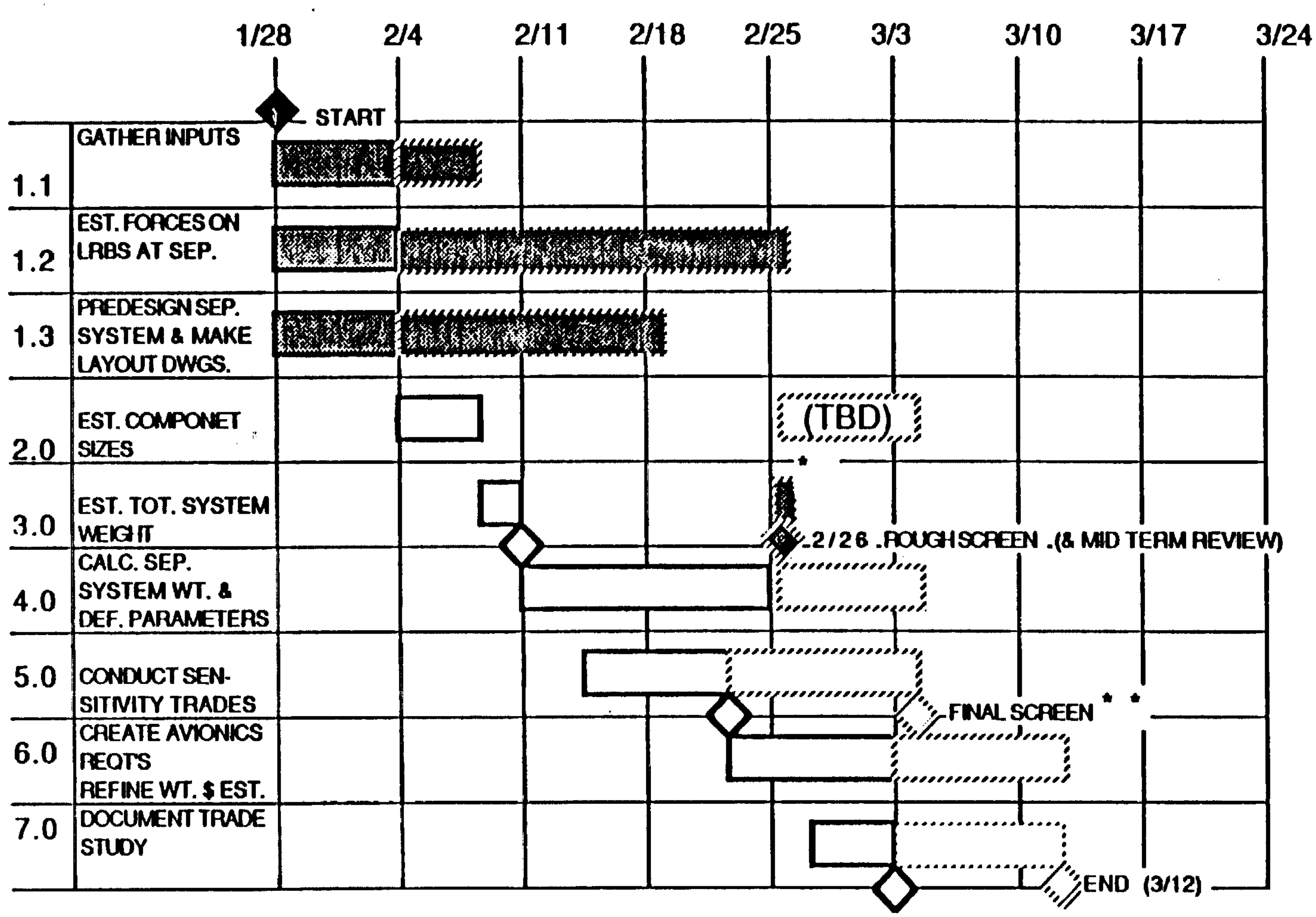
**OTHER TRADES AFFECTED:**

- TRADE 1.3, ABORT MODE OPTIMIZATION (MAY AFFECT CONCLUSIONS)
- TRADE 2.2, MANUAL OVERIDE OPTIONS
- TRADE 2.3, AVIONICS - LEVEL OF REDUNDANCY
- TRADE 2.4, DEGREE OF AUTOMATION




# 1.16 SEPARATION SYSTEM SELECTION TRADE STUDY - OVERALL PLAN

# 1.16 SEPARATION SYSTEM SELECTION - TASK TIME LINE (MODIFIED)




* WEIGHT ESTIMATE DERIVED FOR BSMs ONLY

** ONLY ONE OPTION REMAINS (SOLID ROCKET MOTORS)

= ORIGINAL PLAN

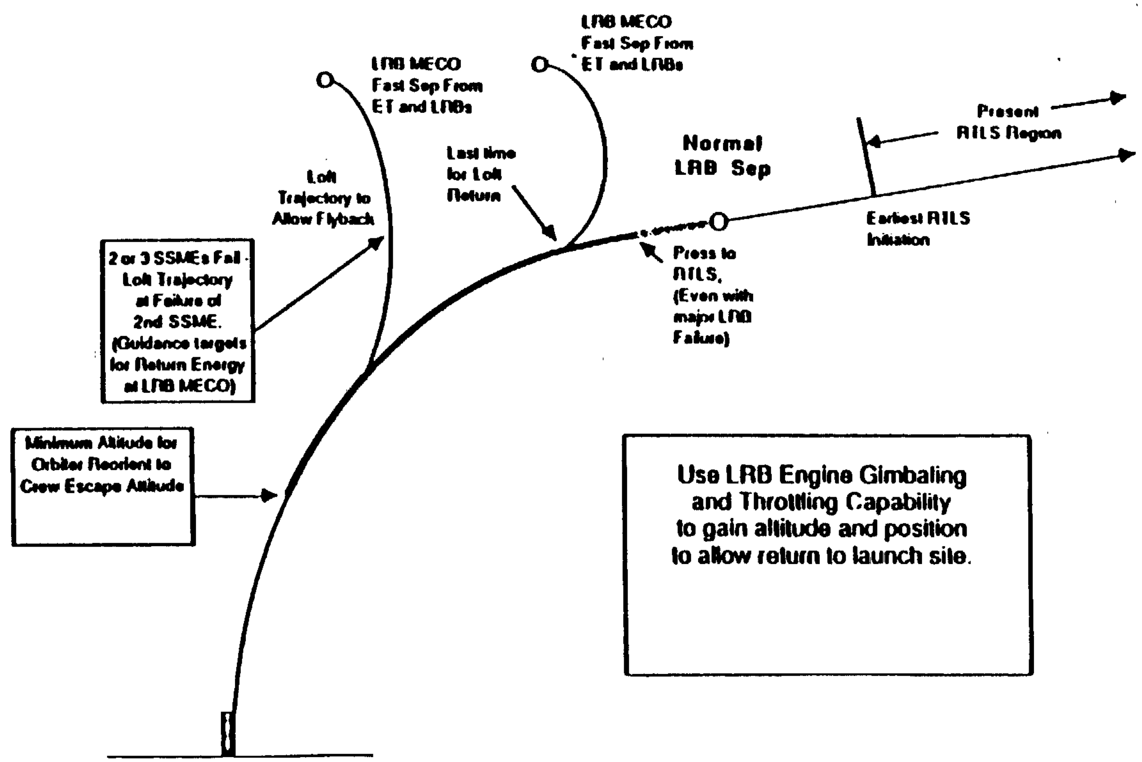
= REVISED PLAN

# TRADE STUDY 1.16 - SEPARATION SYSTEM SELECTION

## Issues

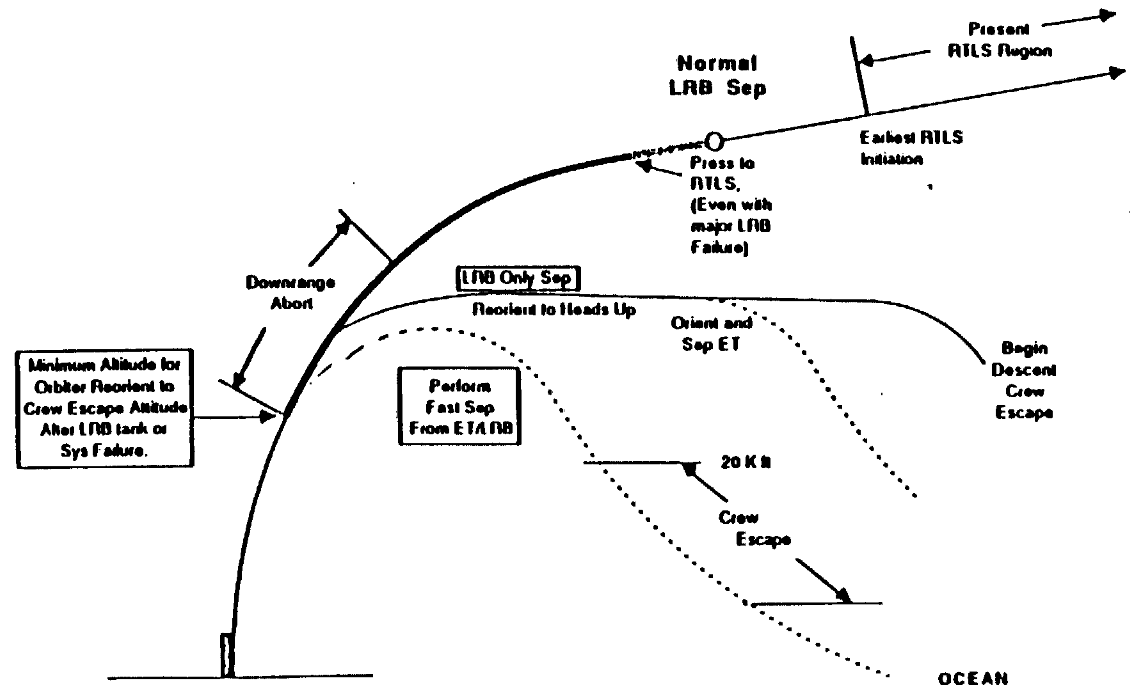
- Earliest Time Desired To Have Separation Capability
  - Normal Separation
  - Earliest Press To RTLS
  - Earliest Downrange (Ocean Ditch) Contingency Abort
  - Warning Times (Detection+Evaluation) For Abort Cases
- Separation Forces
  - Large Dynamic Pressures At Separation
  - Booster Weight at Separation Large For Abort Cases
  - LRBs Develop Greater Aerodynamic Forces
- Vehicle Control During Separation
  - Alpha, Beta, Flight Path Angles May Be Different than SRB's
  - Thrust Mismatch During Shutdown
  - Propellant Slosh Motions
  - Orbiter Engine Out Considerations
- Separation Cue And Sequence
  - State Vector; Fuel Level; Time; On Command (Or Combinations Of These)
  - Incorporating Abort Considerations In Separation Sequence
- Separation Method
  - NSTS BSMs Baselined, But Considering Other Methods
  - Must Provide Acceptable Clearances And Minimal Impingement On Orbiter/ET
- LRB Disposal
  - Range Safety Concerns/Impact Footprint

# TRADE STUDY 1.16 - SEPARATION SYSTEM SELECTION
## Abort Considerations - Orbiter Failures



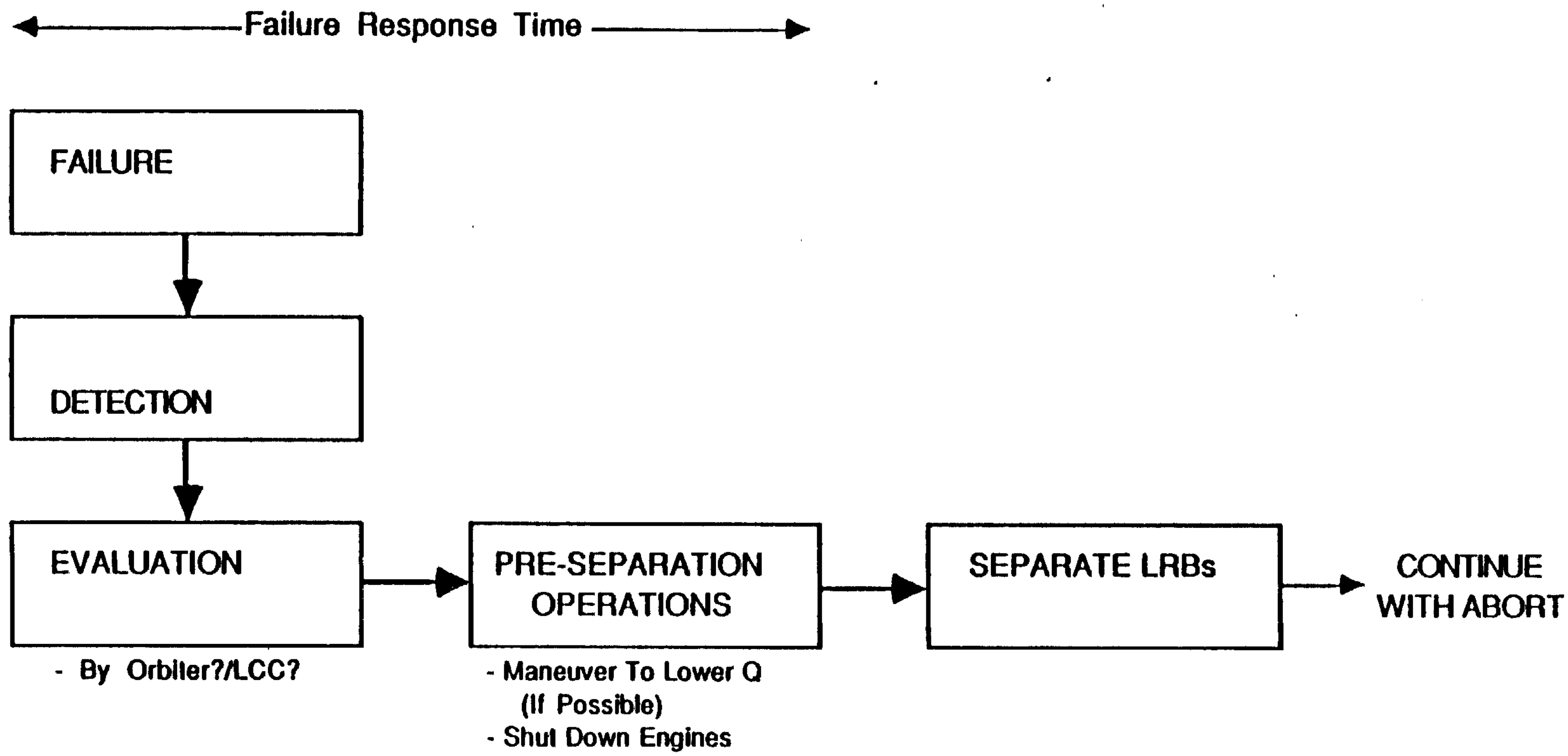

- For Orbiter Failures With LRBs Fully Operational, Contingency Abort Preferred Would Be A 'loft Return' With 'Fast Separation' From ET And LRBs
  - LRB Separation Followed By ET Disposal May Be Substituted For The 'Fast Separation'
  - Further Analysis Of Abort Trajectories Required To Establish Separation Conditions

# TRADE STUDY 1.16 - SEPARATION SYSTEM SELECTION
## Abort Considerations - LRB Failures




- Early Separation Capability Desired To Have 'Press-To-RTLS' Capability
- LRB Separation Improves Survivability Of Downrange Abort (Ocean Ditch) Following Critical LRB Failure
  - Separation Of LRBs Rather Than Fast Separation From ET And LRBs Will Allow More Controlled, Predictable Glide And Descent For Crew Escape

# TRADE STUDY 1.16 - SEPARATION SYSTEM SELECTION
## Abort Considerations - Response Time




- Time-Criticality Of Failure Is An Issue:
  - Time To Separate Should Be Minimized To Reduce Number Of Failures For Which There Is Insufficient Time To Effect Stage Separation
  - Assessment Of Warning Times And Thrust Decay Characteristics Required

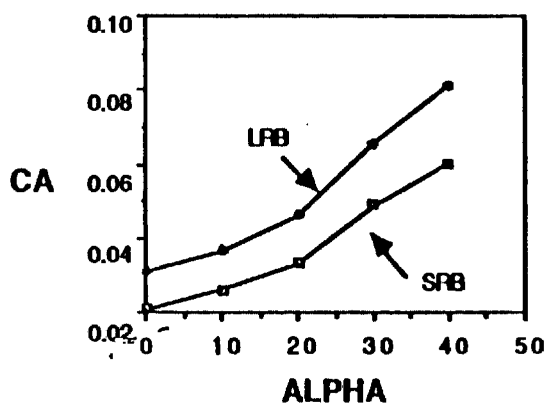
# TRADE STUDY 1.16 - SEPARATION SYSTEM SELECTION
## Design Criteria

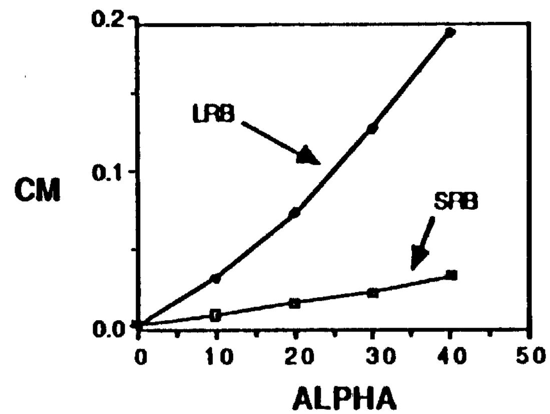
| Condition | Normal | Approx. Earliest Press To RTLS | Approx. Earliest Crew Escape |
|---|---|---|---|
| Time (sec) | 119 | 100 | 75 |
| Altitude (Ft) | 132,250 | 91,420 | 49,850 |
| Mach | 4.5 | 3.35 | 2.0 |
| Dynamic Pressure (Psi) | 81 | 273 | 671 |
| LRB Weight (LBs) | 113,400 | 198,900 | 311,435 |

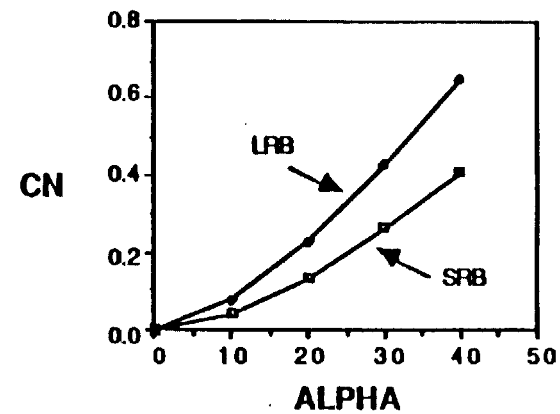
Data For LRB SSME-35 Option 5J (Dec. IPR Version)

- Hardware Design Criteria Will Be Driven By Abort Staging Conditions

# TRADE STUDY1.16 - SEPARATION SYSTEMS SELECTION
## Aero Data Comparison



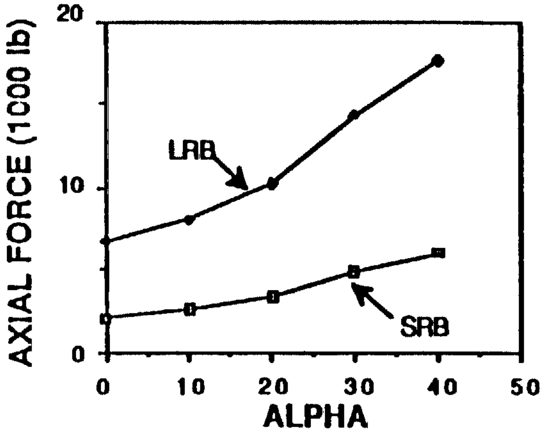

- AERODYNAMIC FORCES GREATER FOR LRB'S THAN FOR SRB'S

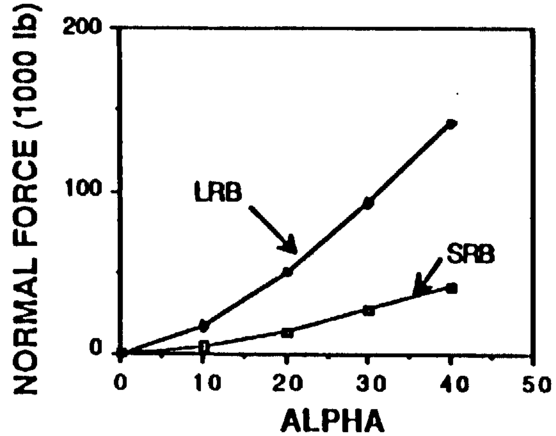
- SEPARATION CONDITIONS COMPARED:

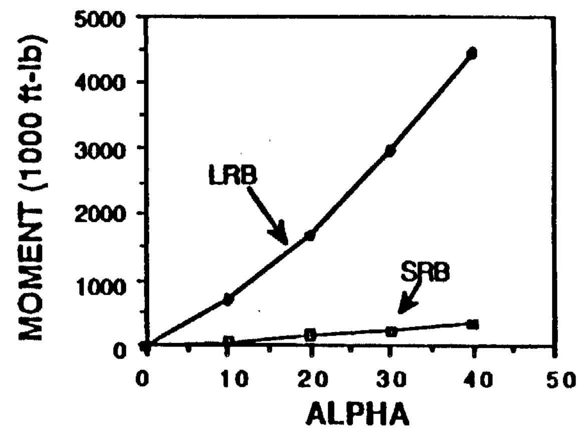
| | 5J LRB (NOMINAL) | SRB (TYPICAL) |
|---|---|---|
| Altitude: | 132,250 ft | 154,000 ft |
| Mach Number: | 4.5 | 4.5 |
| Max Alpha at Staging | (TBD) | ± 15° |

- SHUTTLE REFERENCE DIMENSIONS USED: Area = 2690 ft , Length = 107.525 ft

# TRADE STUDY 1.16 - SEPARATION SYSTEMS SELECTION
## Aero Force Data Comparison for Nominal Separation



# TRADE STUDY 1.16 - SEPARATION SYSTEM SELECTION
## Control Considerations

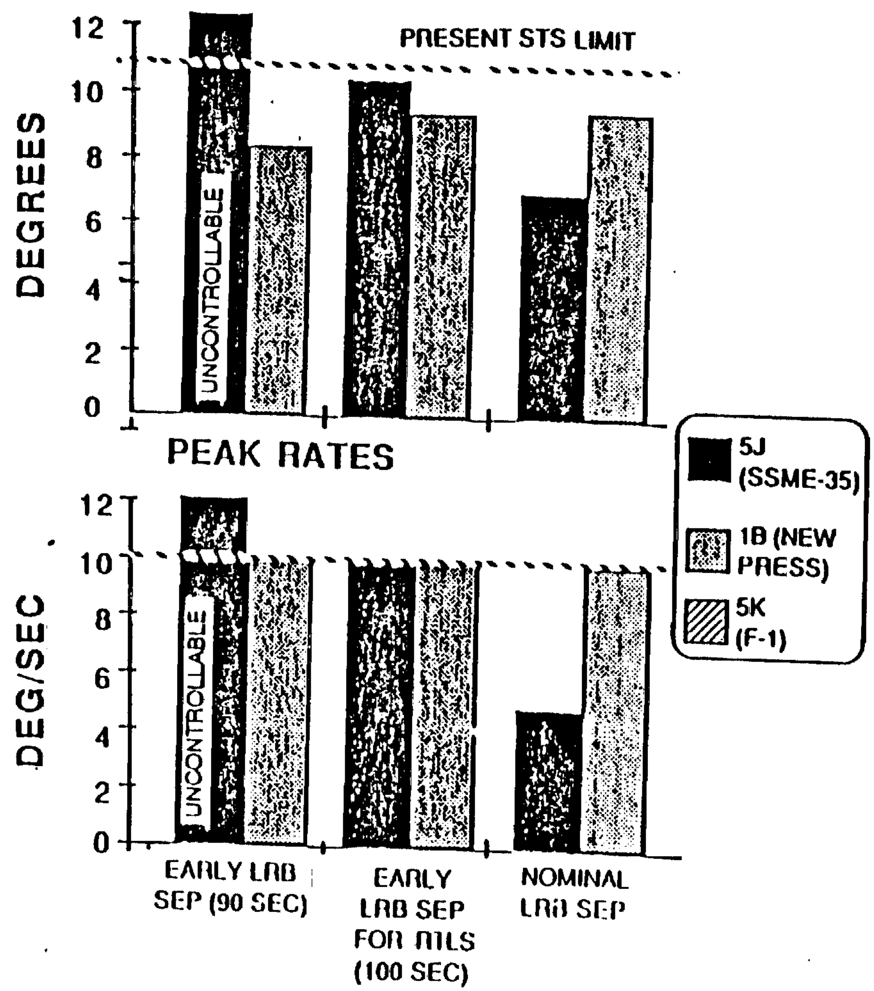
- Currently, SRB Thrust Mismatch During Tailoff Can Saturate Orbiter Control Authority

- Control Authority During LRB Separation For Options 5J (Mid Term Review Version) And 1B Were Examnined
  - 95% "Kennedy" Crosswinds
  - 300,000 Lbf Thrust Decay Differential Between LRBs For Both Options
  - Orbiter SSME's Providing TVC With Deflection Limits Of 11 Degrees, And Rate Limits Of 10 Deg/Sec
  - Nominal, Earliest RTLS, & Earliest Crew Escape Cases Examined For Both Cases

- Orbiter Control Authority Should Be Sufficient (But Further Analysis Req'd)

- Configuration 5J Is Not Controllable With LRB Separation Prior To 100 Seconds (Refer To The Next Two Sheets For Orbiter TVC Deflections And Rates Charts)

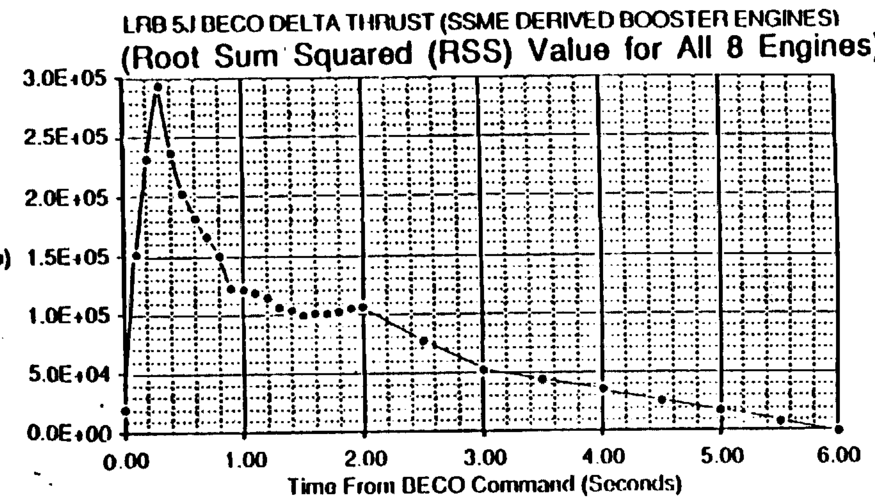
# TRADE STUDY 1.16 - SEPARATION SYSTEM SELECTION
## Control Considerations Con't

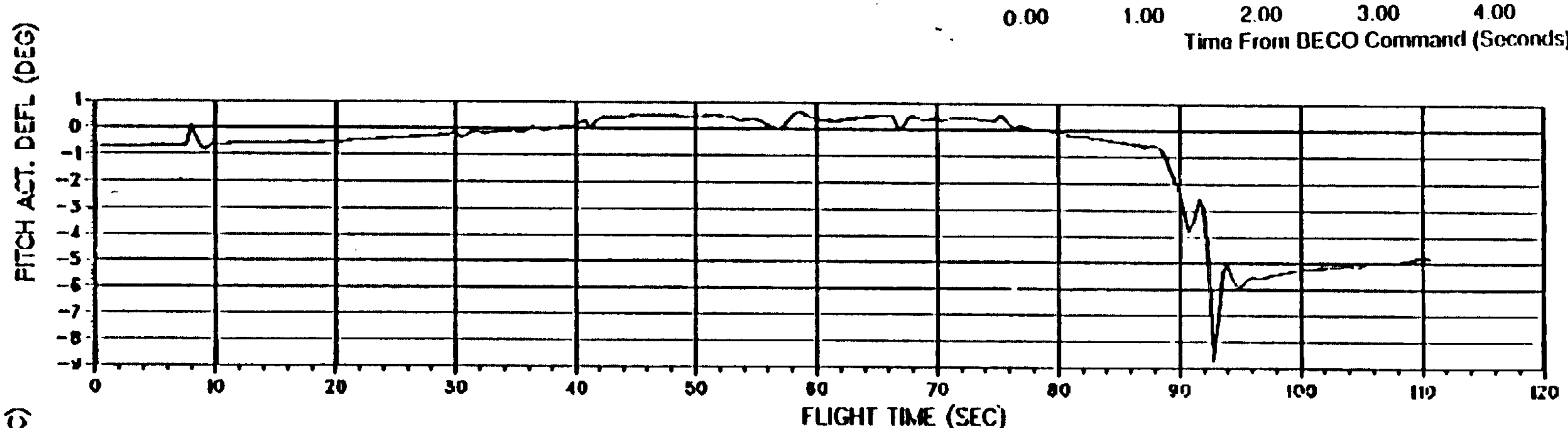


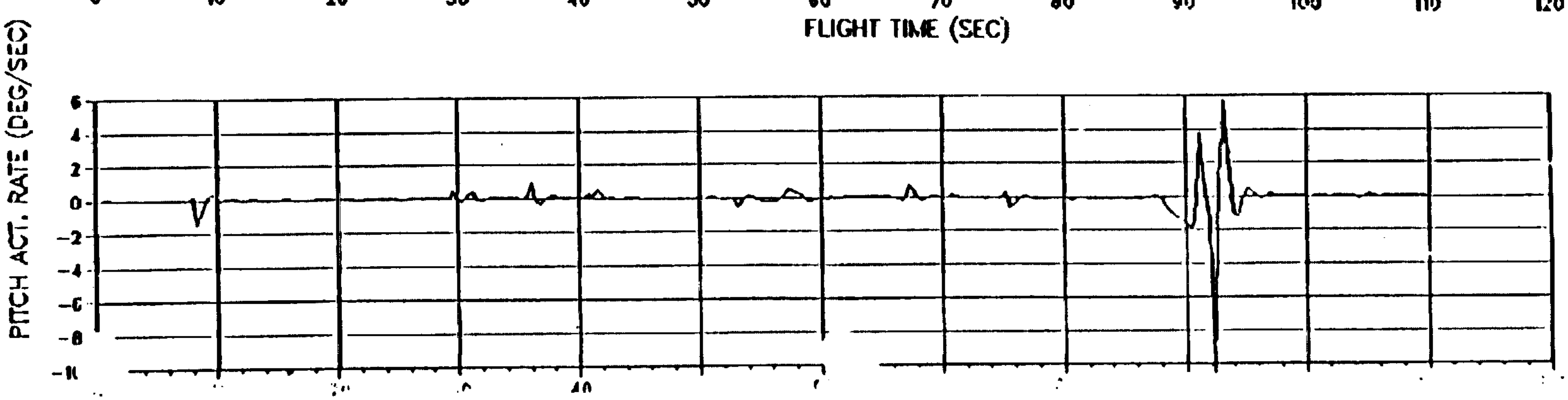
# TRADE STUDY 1.16 - SEPARATION SYSTEM SELECTION

## Control Considerations Con't

- Results For Approximate Earliest Crew Escape Abort
  - Time= 92 Sec.
  - Max Pitch Gimbal Angle = -8.7 Deg (SSME Max = ± 11 Deg)
  - Max Yaw Gimbal Rate = 10.0 Deg/Sec (SSME Max = ±10 Deg/Sec)

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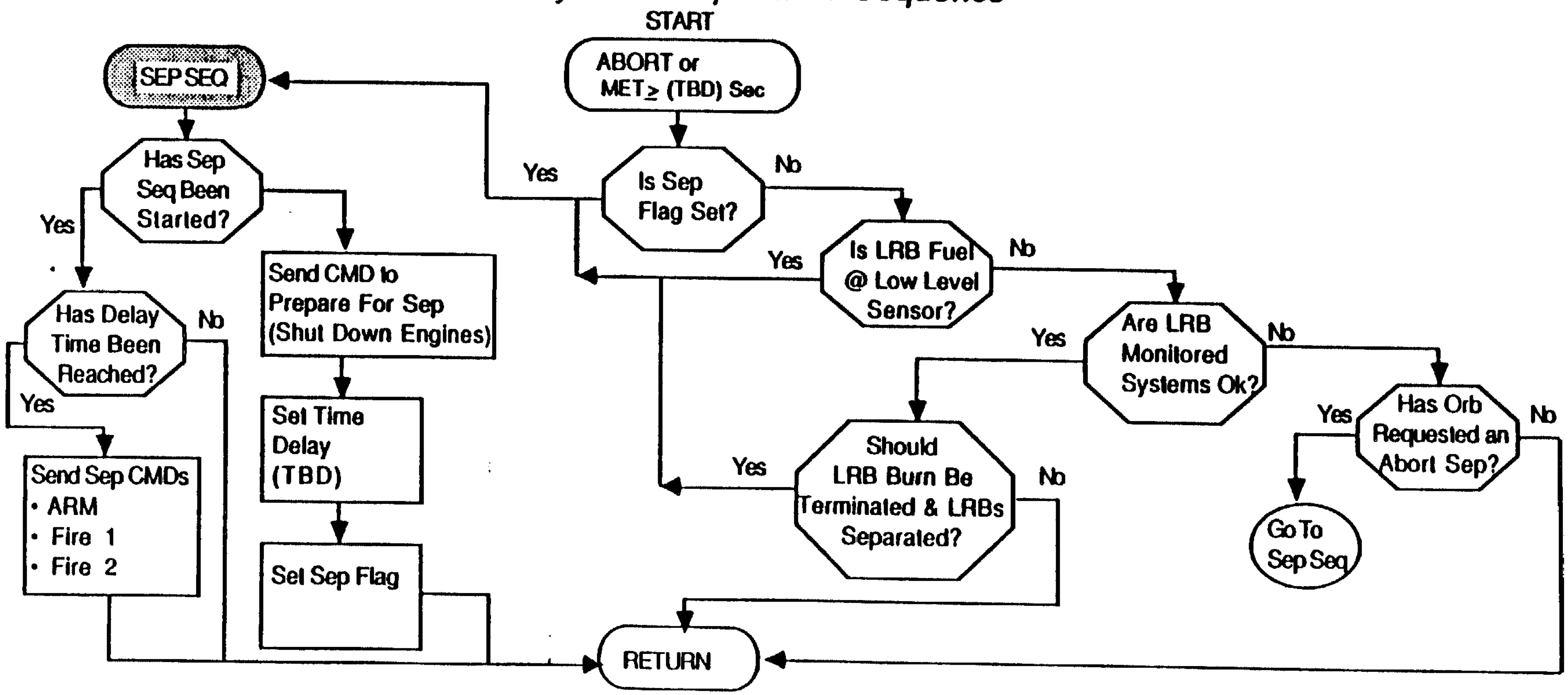
# TRADE STUDY 1.16 - SEPARATION SYSTEM SELECTION
## Separation Cue And Sequence

- SRB Separation Cued On SRB Chamber Pressure Decay (Initiated at Pc= 50 PSIA)
- LRB Separation 'Cue' Determination Still In Work; Preliminary Investigation Indicates 'Cue' To Be Based Upon 'Low Fuel Level Sensor'
  - Assures Engines Will Not Be Run Dry
  - Will Require That LRBs Designed With Flight Performance Reserves (FPRs) To Meet Desired State Vector (Velocity And Position) Under Worst Case Scenarios, Or That Orbiter Second Stage Burn Makes-up Any Shortage In First Stage Performance

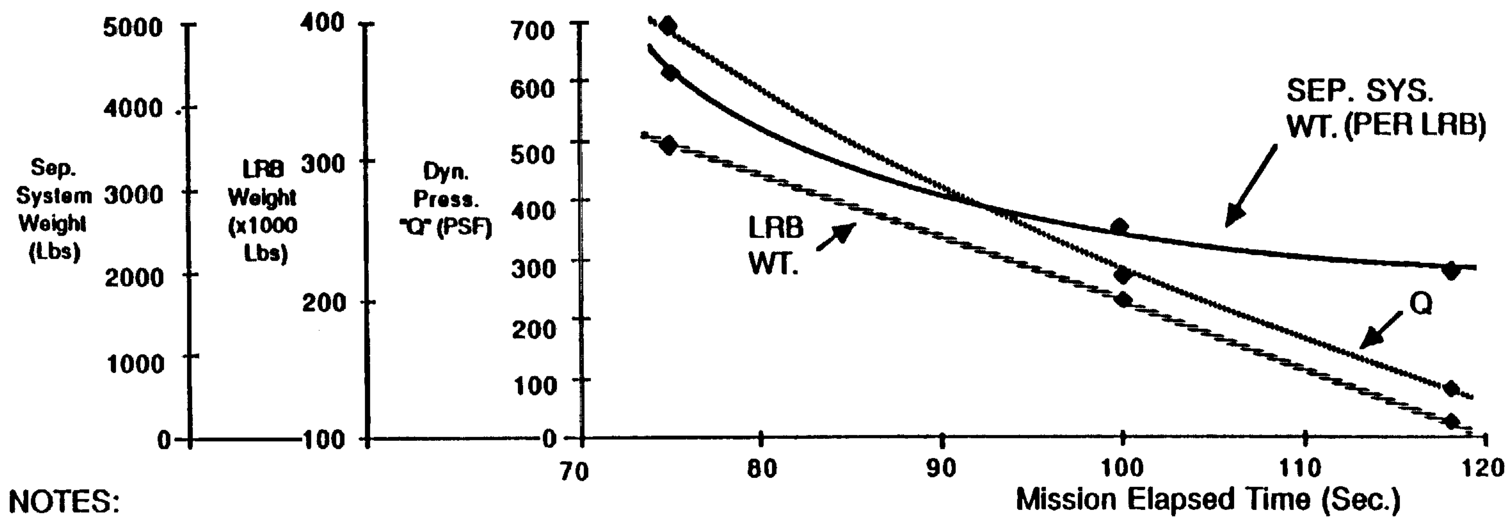
*Preliminary LRB Separation Sequence*



# TRADE STUDY 1.16 - SEPARATION SYSTEM SELECTION
## System Weight Trend

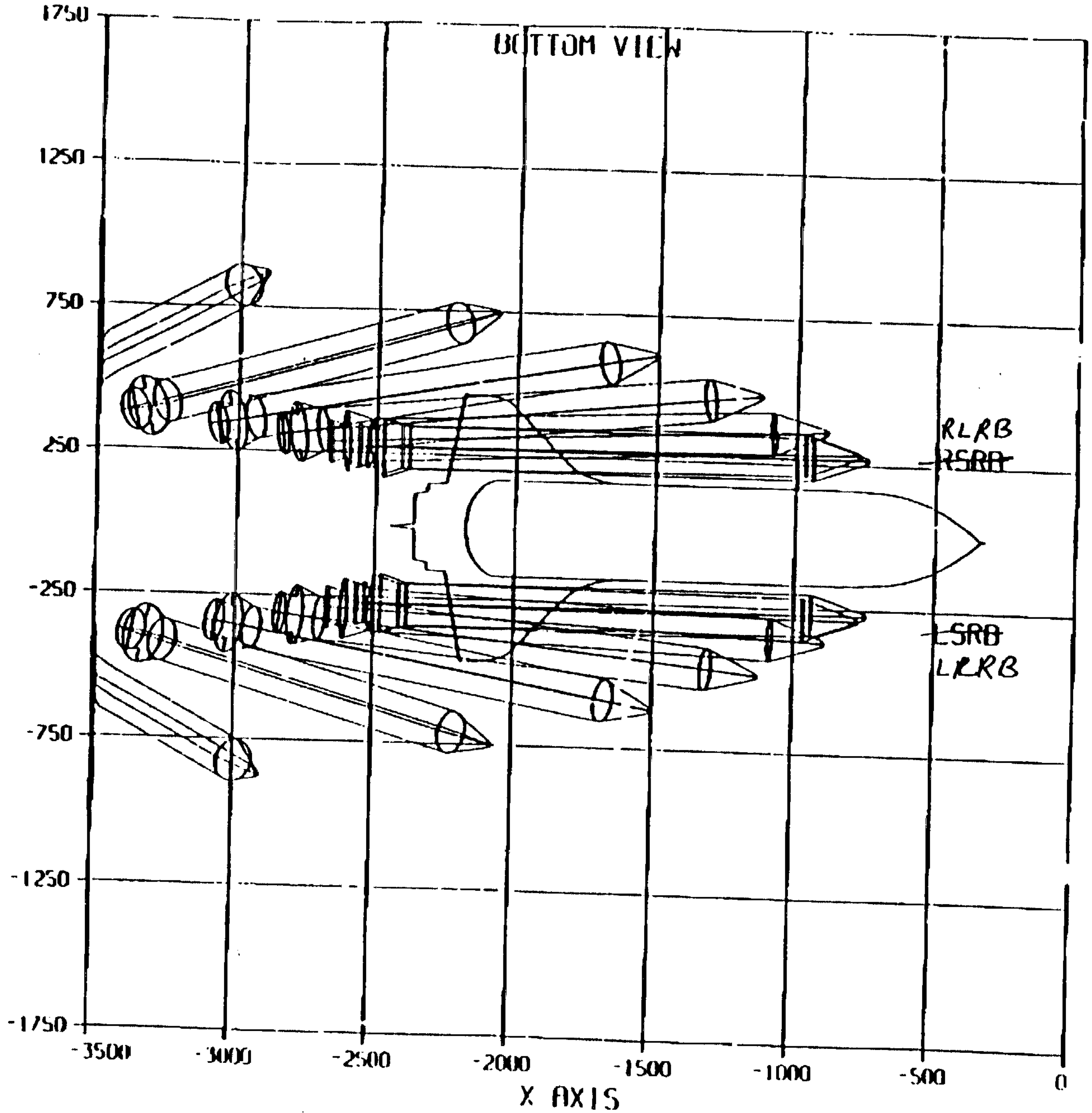
| |
|---|
| **OPTION:** Current NSTS BSMs |
| **AVERAGE THRUST PER BSM:** 18,500 LBf (min) (30-100 °F) |
| **TOTAL IMPULSE PER BSM:** 15,000 LBf•Sec (30-100 °F) |
| **ORIENTATION:** Same Angles And Mounting Scheme As SRBs* |
| **TOTAL BSMS REQ'D FOR SAFE SEPARATION** |
| **NOMINAL (118 SEC)** FWD: 4+Margin=6 AFT: 4+Margin=6 |
| **RTLS (~100 SEC)** FWD: 6+Margin=9 AFT: 6+Margin=9 |
| **CREW ESCAPE (~75 SEC)** FWD: 11+Margin=17 AFT: 6+Margin=9 |

* To Be Optimized




NOTES:
- NASA Program SVDS Used To Evaluate Separation Dynamics & Clearances
- Nominal SRB Aerodynamic Interference Effects Used
- Free Stream LRB Element Aero Predicted With The Program: "USAF AUTOMATED MISSILE DATCOM * REV 11/85"
- LO2/LH2 SSME-35 LRB Option (December IPR Version) Used
- 5 Deg/Sec Roll Rate, 2 Deg/Sec Pitch Rate, And 2 Deg/Sec Yaw Rate Evaluated
- Alpha = +10 Degrees, And Beta = +10 Degrees Evaluated
- Weight Scaling Based On Number Of BSMs Req'd
- Number Of BSMs Req'd Multiplied By 1.5 As A Margin For Uncertanties
- All Orbiter SSMEs running

LRB SEPARATION 5J NOMINAL T=11[illegible] [illegible]C
4F,4A BSM $\alpha=\beta=0$ P,Q,R=0.,0.,0. SEP [illegible]



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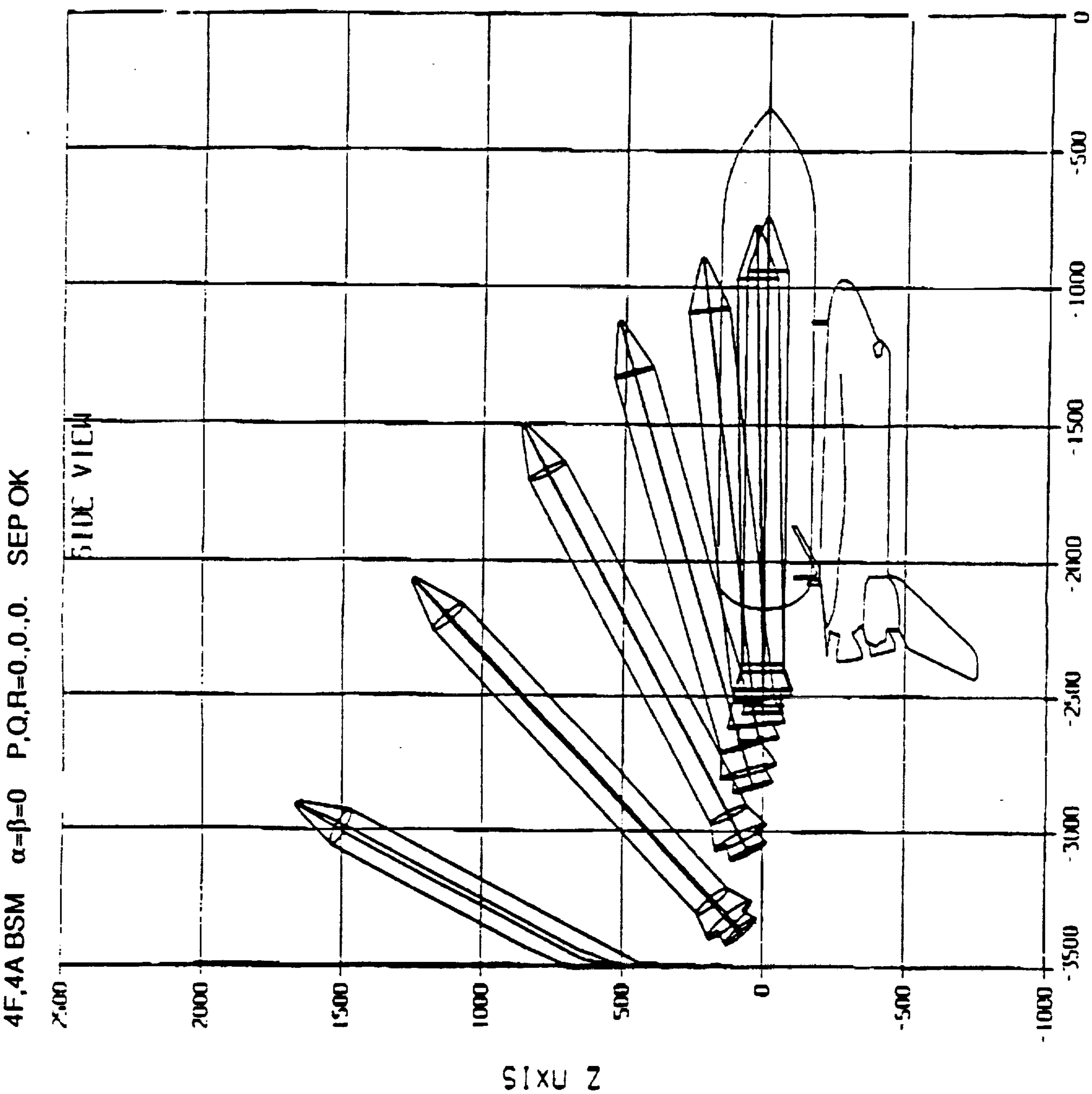
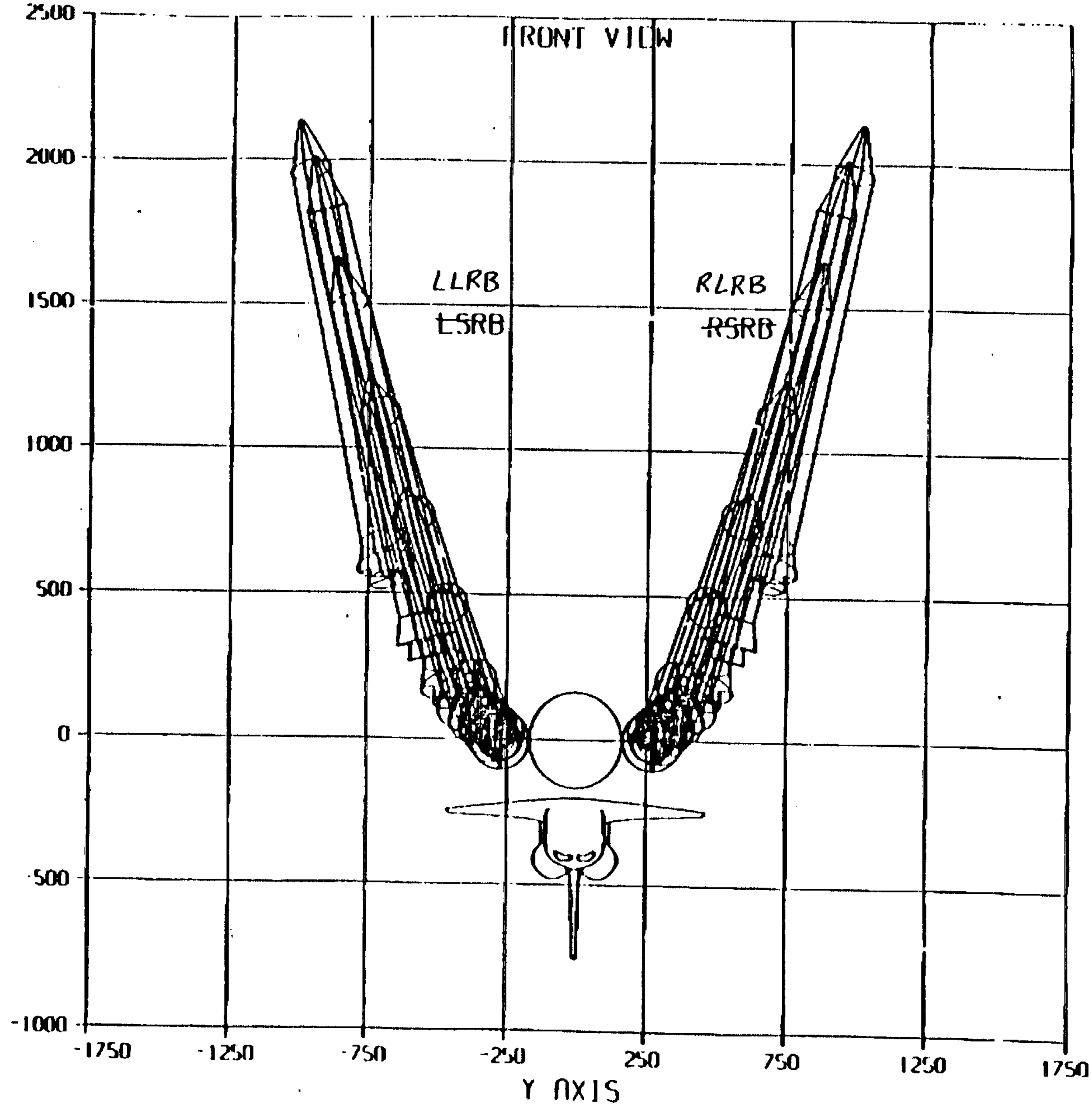
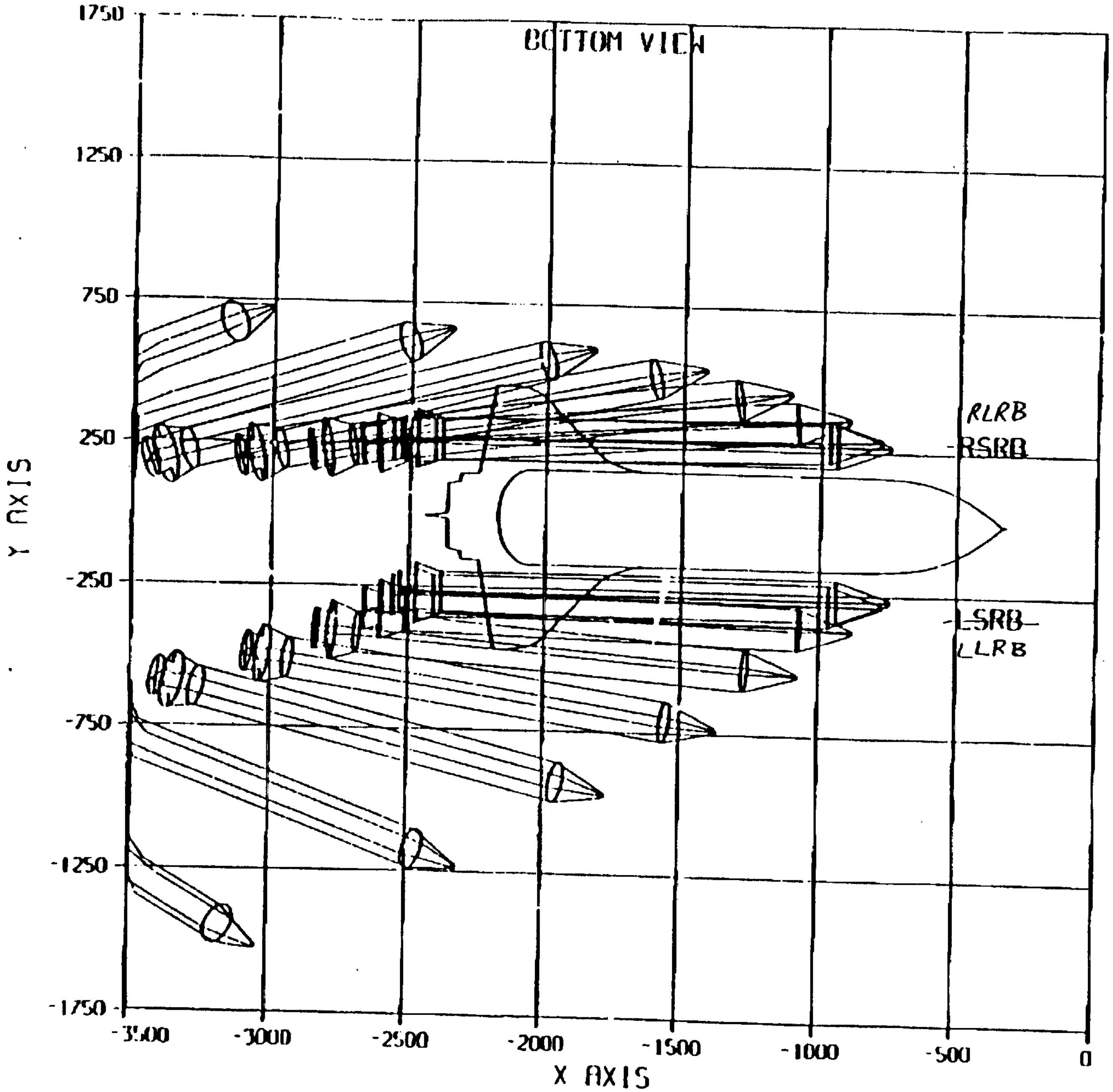


LRB SEPARATION 5J NOMINA T=119 SEC
4F,4A BSM $\alpha=\beta=0$ P,Q,R=0.,0.,0. SEP OK



4F,4A BSM $\alpha=\beta=10$ P,Q,R=5.,2.,2. SEP OK



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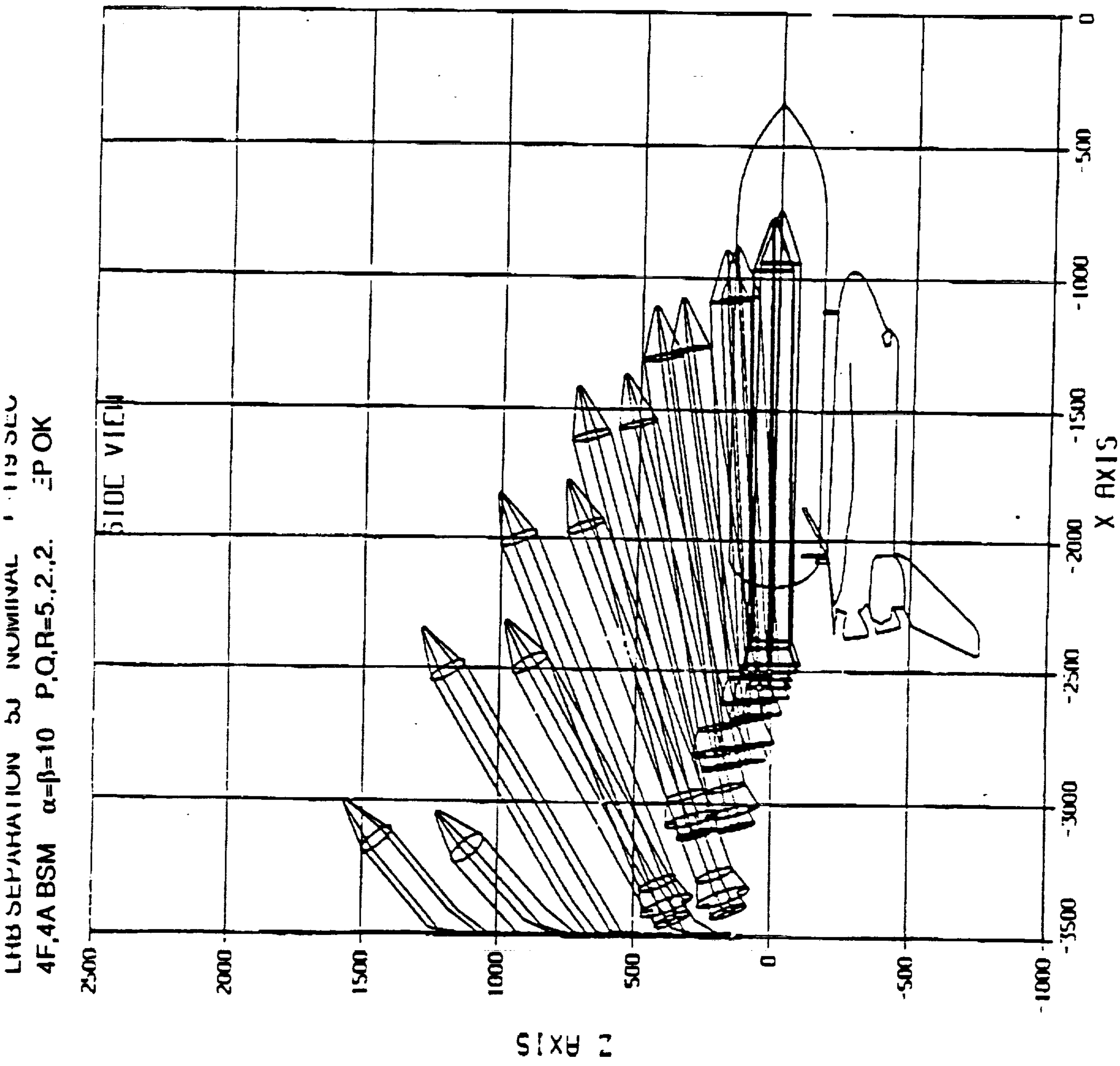
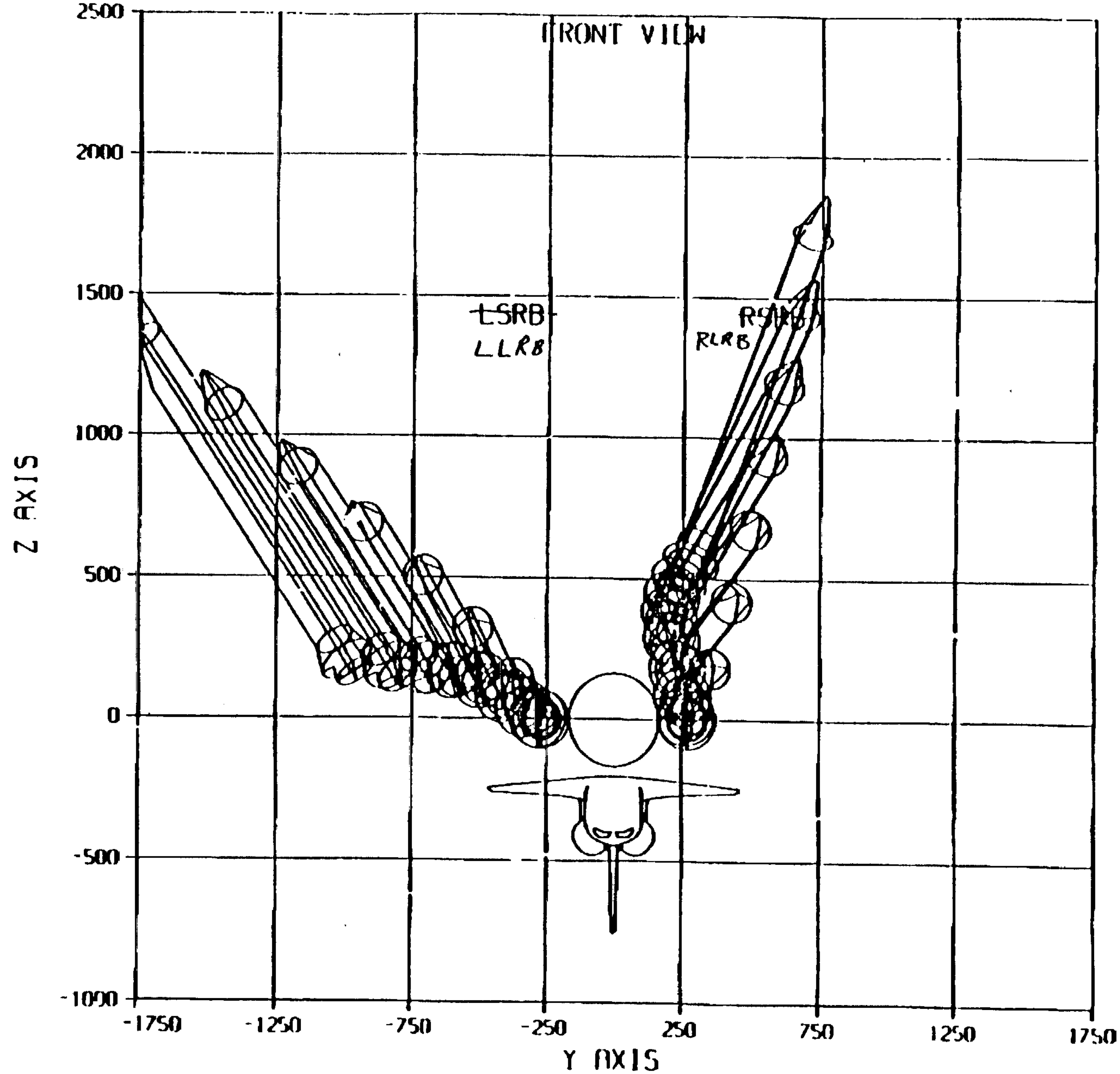


LRB SEPARATION 5J NOMINAL T=119 SEC
4F,4A BSM α=β=10 P,Q,R=5.,2.,2. SEP OK



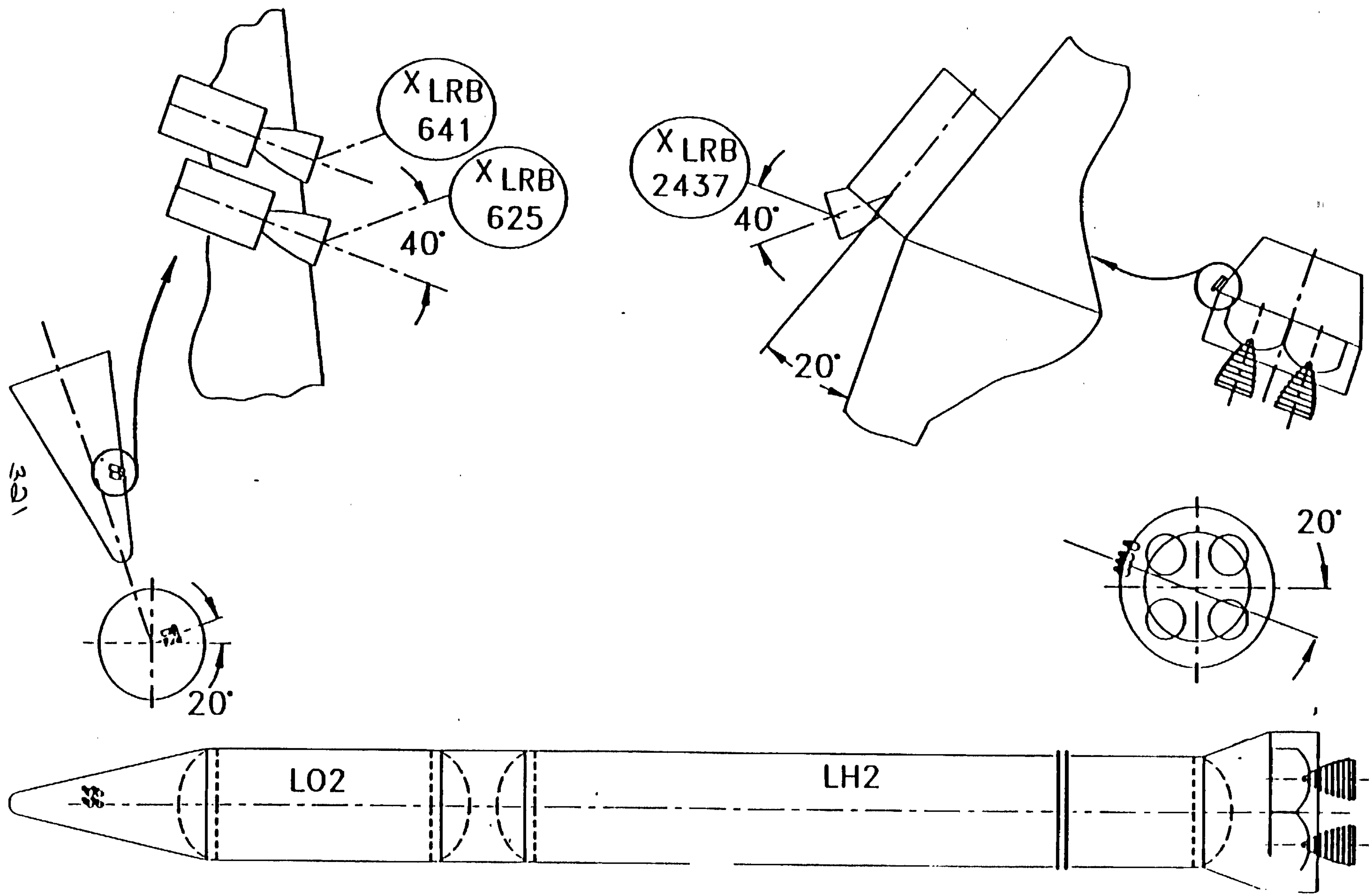
# TRADE 1.16: SEPARATION SELECTION SELECTION
## Option Evaluation Summmary

| OPTION | | EVALUATION CRITERIA | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | SAFETY | RELIABILITY | STS INTEGRATION | PERFORMANCE (SYSTEM WT.) | COST | PROGRAM RISK | IMPINGEMENT ON OBITER | GROWTH |
| 1.1 A | NSTS BSMs | + | + | + | + | + | + | - | 0 |
| 1.1 B | New Solid BSMs | + | + | + | + Optimize For LRBs | 0 | + | - | 0 |
| 1.2.1 | Motors using LRB Tank Propellants | 0 | - | 0 | - | - | - | + | + |
| 1.2.2 A | Motors using Hypergolics | - | 0 | 0 | - | - | - | + | + |
| 1.2.2 B | New Liquid BSMs | 0 | 0 | + | + | 0 | + | + | 0 |
| 2.1 | Spring Thrusters | + | 0 | - ET Mods | - | 0 | 0 | + | 0 |
| 2.2 | Pneumatic Thrusters | + | - | - ET Mods | - | 0 | 0 | + | 0 |
| 3.0 | Pressure Bleed From He Tank | + | 0 | 0 | 0 | 0 | - | + | + |

- ORIGINAL ROCKWELL TRADE STUDY IN 1973 RE-EXAMINED
- CURSORY EXAMINATION OF OPTIONS INDICATES BSMs PREFERRED

NOTE: KINEMATIC SYSTEMS NOT INVESTIGATED DUE TO ET MODS REQ'D

# SOLID ROCKET MOTOR SEPARATION OPTION

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# Option Evaluation Sheet

**Option 1.1 (A):** Separation Motors - Solid Propellant (Existing NSTS BSM's)

**Description:**

**Total required for safe separation:**
**Normal:** (TBD)  **RTLS:** (TBD)  **Down Range Abort:** (TBD)
**Location:** Forward Frustrum & Aft Skirt
**Orientation:** Current BSM orientation (To Be Optimized)
**Thrust:** 21,680 Lb (vac) per BSM
**Total Impulse:** 14,760 Lb-sec per BSM
**System Weight*:** 168 Lb per BSM
**System Costs*:**
**DDT&E:** (Shuttle Ref 11.7 $M)  **Reccuring:** ??



**Qualitative Evaluation:**

PRO:
- Least complex of options considered
- Highly reliable
- Flight qualified for STS, low cost and risk
- Fast response time
- Can be resized or additional BSMs added for higher thrust requirements and for redundancy considerations
- Simple, minimal Avionics/Commands; no active control

CON:
- Exhaust plume possibly detrimental to the Orbiter TPS

* For Normal Separation

# Option Evaluation Sheet

**Option 1.1 (B):** Separation Motors - Solid Propellant (New; LRB-Optimized)

**Description:**

**Total required for safe separation:**
**Normal:** (TBD) **RTLS:** (TBD) **Down Range Abort:** (TBD)
**Location:** Forward Frustrum & Aft Skirt
**Orientation:** Current BSM orientation (To Be Optimized)
**Thrust:** (TBD) per BSM
**Total Impulse:** (TBD) per BSM
**System Weight*:** (TBD) per BSM
**System Costs*:**
**DDT&E:**Shuttle Ref. $11.7 M **Reccuring:** (TBD)

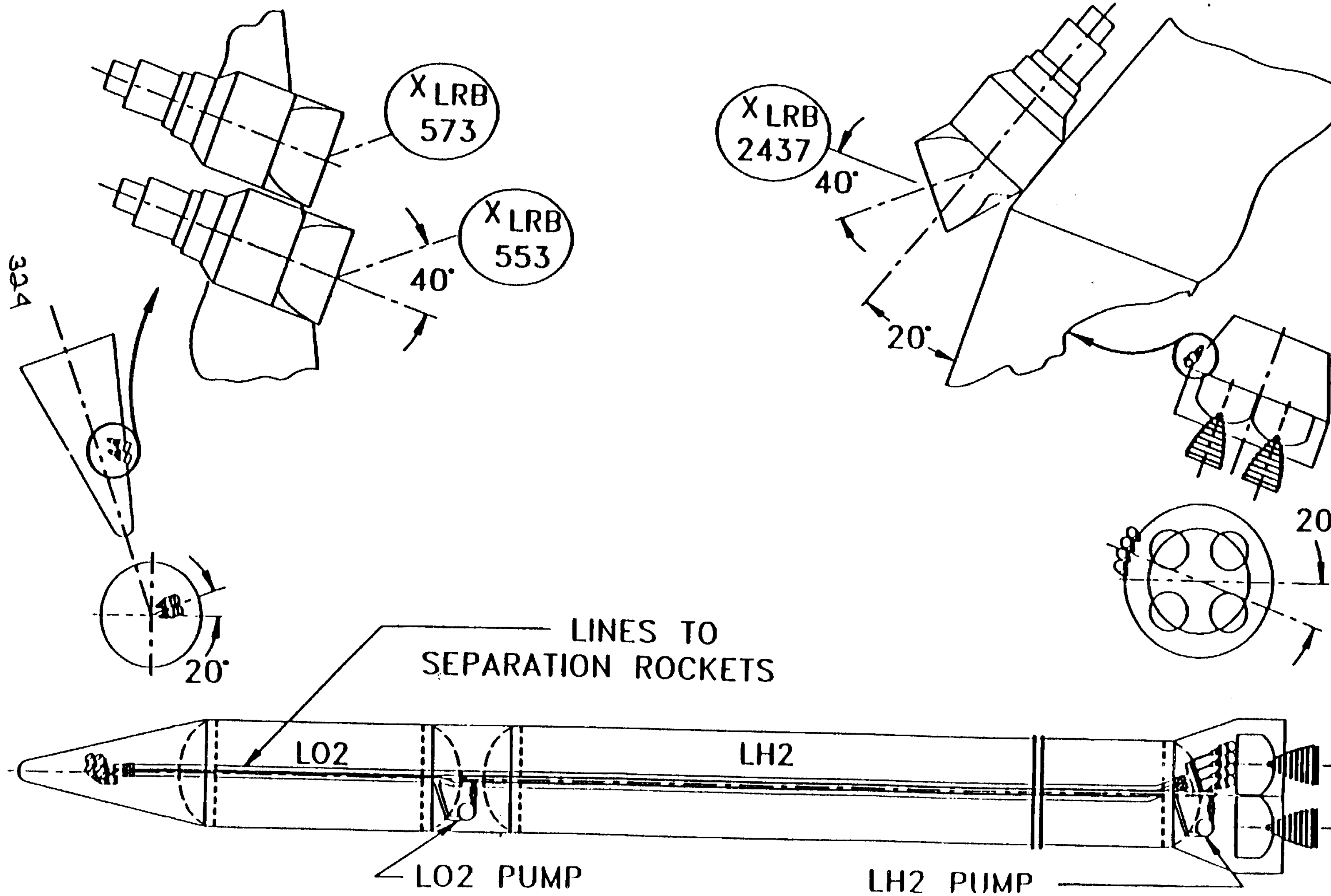
**Qualitative Evaluation:**

PRO:
- Can be optimized for LRB requirements
- Simple - Based on NSTS BSM's
- Simple, minimal avionics/commands; no active control
- Low cost and risk
- Fast response time
- Possiblity of eliminating aluminum content of exhaust (new propellant)

CON:
- Exhaust plume possibly detrimental to the Orbiter TPS
- Need qualification, greater cost to develop than BSM's

* For Normal Separation

# LIQUID ROCKET MOTOR SEPARATION OPTION (PROPELLANTS FROM LRB)

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# Option Evaluation Sheet

**Option 1.2.1:** Separation Motors - Liquid Propellants (Drawn From LRB Tanks)

**Description:**

**Location:** Forward Frustrum & Aft Skirt (To Be Optimized)
**Orientation:** Current BSM orientation (To Be Optimized)
**Thrust:** (TBD - Expected to be 10-50 KLb) per BSM
**Total Impulse:** (TBD) per BSM
**System Weight*:** (TBD) per BSM
**System Costs*:**
**DDT&E:** (TBD) **Reccuring:** (TBD)

NOTE: Propellants would need to be drawn from main propellant feedlines at aft end of tanks to avoid vapor pull-through

**Qualitative Evaluation:**

PRO:
- Can vary burn time and thrust
- Possible reusability
- Less Orbiter TPS damage concern because plume has lower temperature and no solid particulates

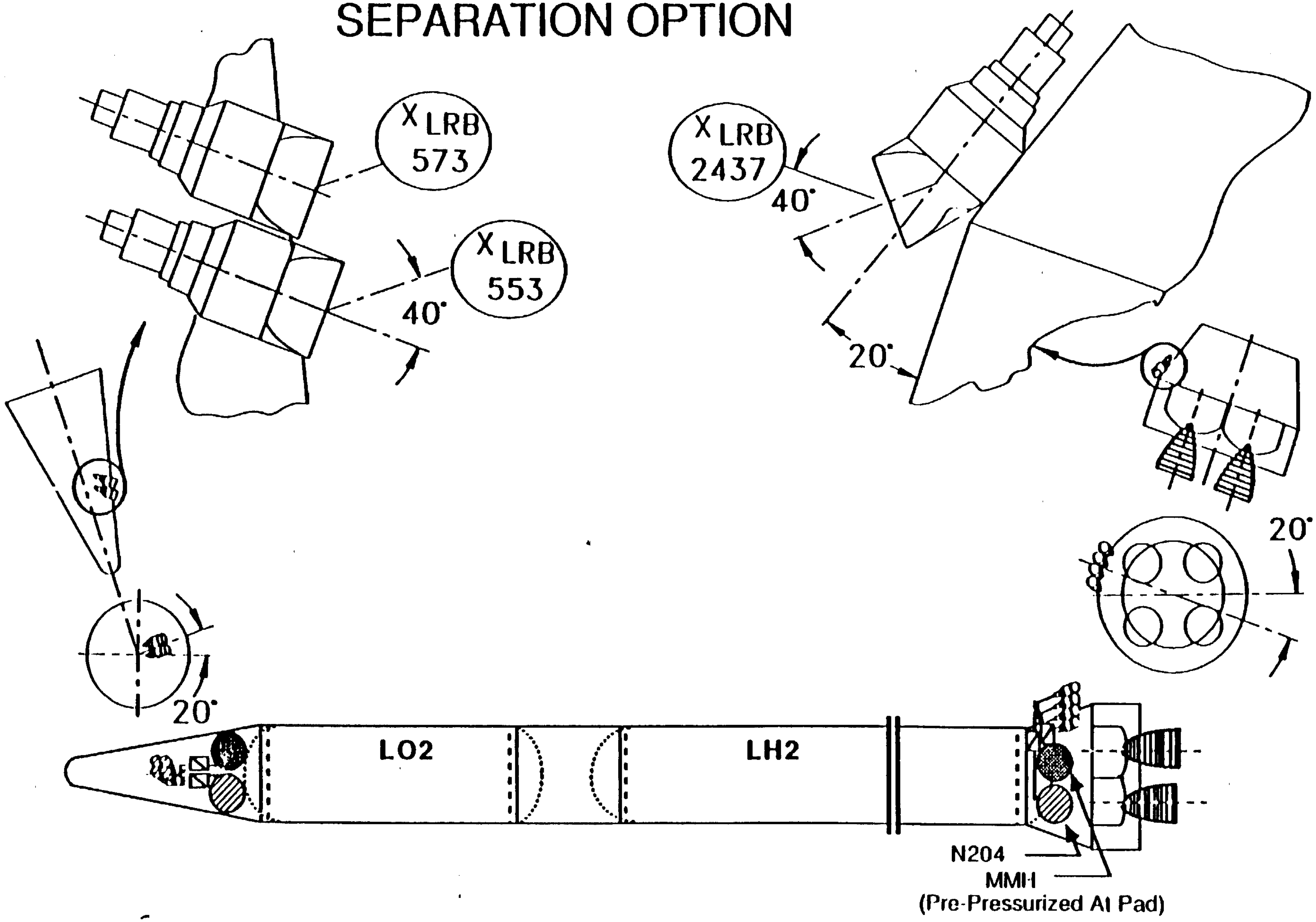
* For Normal Separation

1 ^ 1 Evaluation Con't

CON:

- Separation system intimately linked to main propulsion system; i.e.; main system failure jeopardizes separation capability
- Complex system imposes high cost, technical and schedule risk, hardware/software complexity and lower system reliability
- LO2/LH2 or LO2/RP-1 engines are large, requiring complex operations (purge, chilldown, etc.)
- Longer thrust rise time compared to solid motors
- Engines, presumably pressure-fed, would require DDT&E because such engines are not currently available
- Large system weight due to numerous pumps, valves, lines and power source needed to run the pumps
- Active control of fluid systems required. Acitive monitoring needs to be integrated with flight system. Avionics requirements estimated to be 10-15 times as great as NSTS BSMs

# LIQUID ROCKET MOTOR SEPARATION OPTION



# Option Evaluation Sheet

**Option 1.2.2 (A) : Separation Motors - Liquid Propellants (Stored Elsewhere)**

**Description:**

**Location:** Forward Frustrum & Aft Skirt (To Be Optimized)
**Orientation:** Current BSM orientation (To Be Optimized)
**Thrust:** (TBD - Expected to be 10-50 KLb) per BSM
**Total Impulse:** (TBD) per BSM
**System Weight***: (TBD) per BSM
**System Costs***:
**DDT&E:** (TBD) **Reccuring:** (TBD)

**Qualitative Evaluation:**

PRO:
- Can vary burn time and thrust
- Possible reusability
- Less Orbiter TPS damage concern because plume has lower temperature and no solid particulates
- Hypergolic pressure-fed engines in the 10-20 Klb range have been tested by TRW
- Time from ingition to maximum thrust for the hydrazine fueled motor can be very short

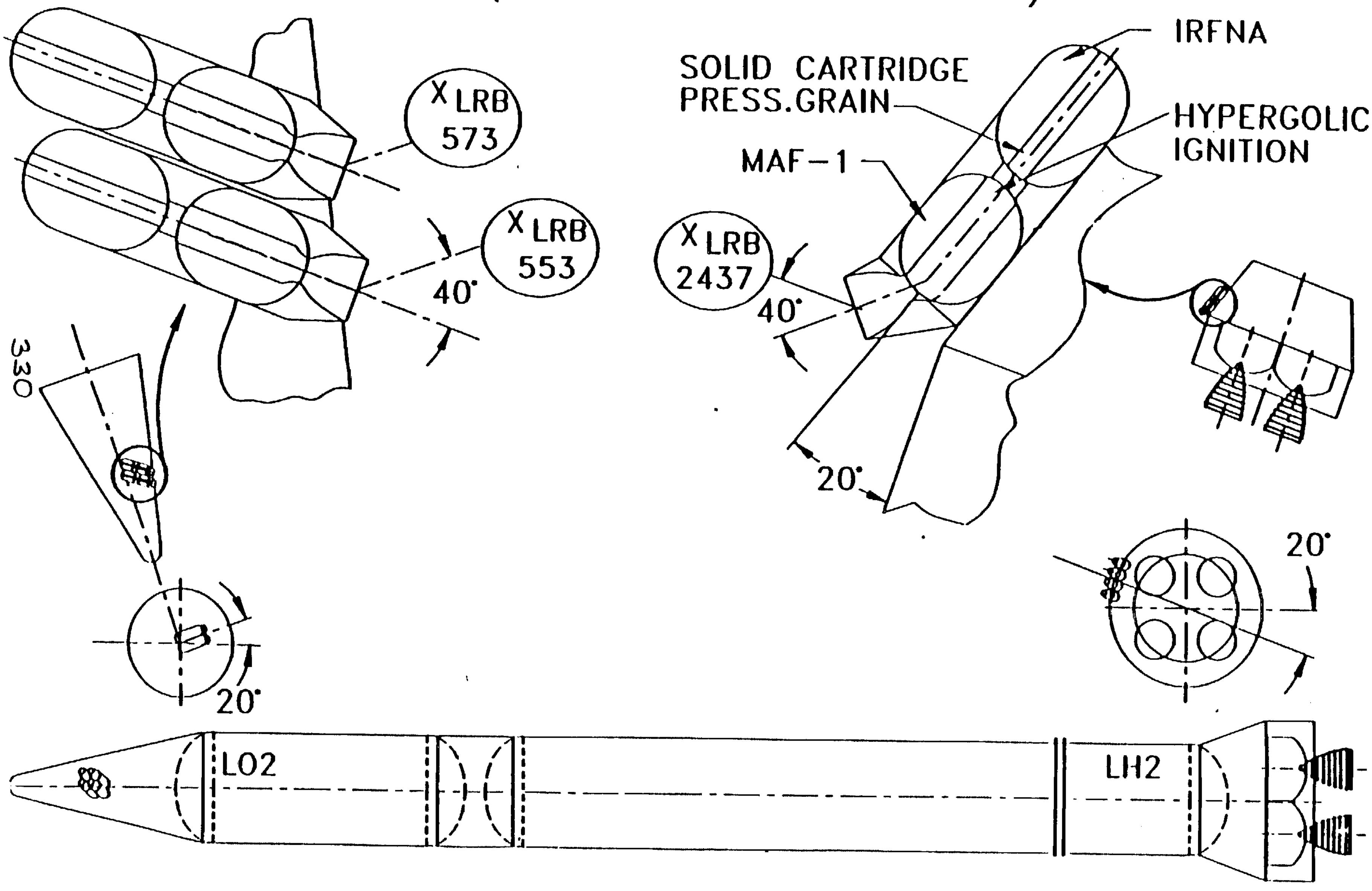
* For Normal Separation

1.2.2 (A) Evaluation Con't

CON:

- Propellants likely to be hydrazine or hypergols with their associated safety hazards (explosiveness in air, toxicity)
- Separate propellant bottles at high pressure would be required for the forward and aft motors, although they may be built-in with engine as a single module
- The whole separation system would need to be developed, tested and qualified
- Increased weight over NSTS BSM system due to additional tankage, valves and lines
- System volume requirement larger than BSM's

# LIQUID ROCKET MOTOR SEPARATION OPTION (INTEGRAL PROPELLANTS)



# Option Evaluation Sheet

**Option 1.2.2 (B)** : Separation Motors - Liquid Propellants (Integrated Propellants) - Note: Rockwell concept shown

**Description:**

**Total required for safe separation:**
**Normal:** (TBD) **RTLS:** (TBD) **Down Range Abort:** (TBD)
**Location:** Forward Frustrum & Aft Skirt (To Be Optimized)
**Orientation:** Current BSM orientation (To Be Optimized)
**Thrust:** (TBD - Expected to be 10-50 KLb) per BSM
**Total Impulse:** (TBD) per BSM
**System Weight***: (TBD) per BSM
**System Costs***:
**DDT&E:** (TBD) **Reccuring:** (TBD)

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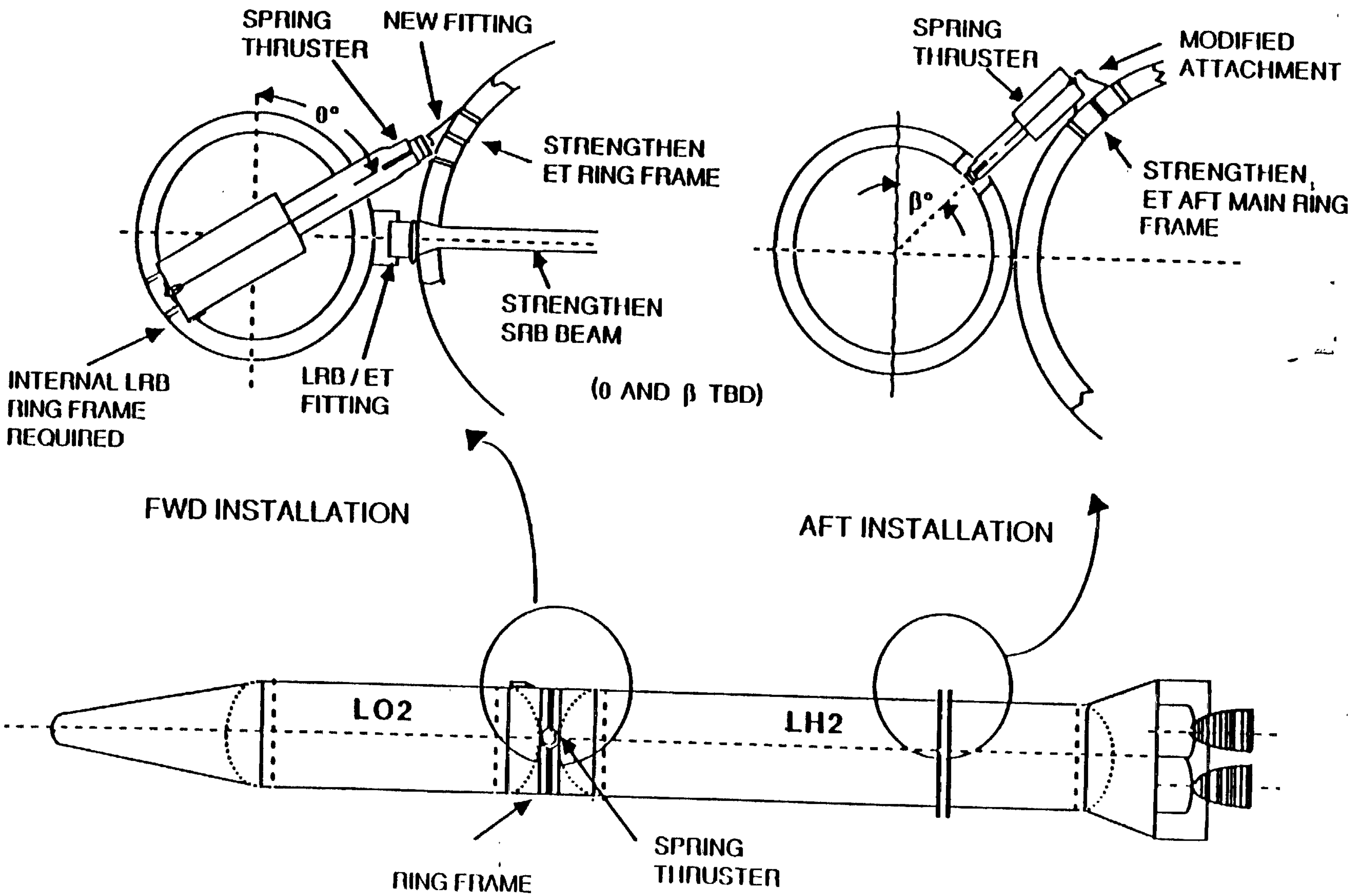
**Qualitative Evaluation:**

PRO:
- Can be designed in compact propulsion modules
- Can be optimized for LRB requirements
- Less Orbiter TPS damage concern because plume has lower temperature and no solid particulates
- Can vary burn time and thrust

CON:
- Propellant safety issues
- Complex design requiring larger DDT&E than BSM's
- Larger overall system weight than NSTS BSM's (≈50% greater than BSM's for same thrust level)
- May require monitoring of propellants

# SEPARATION OPTIONS

## MECHANICAL SEPARATION SYSTEM (FWD & AFT SPRING THRUSTERS)

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# Option Evaluation Sheet

**Option 2.1 (A) : Spring Thrusters (FWD Spring Thruster Located in Intertank)**

**Description:**

**Location:** FWD in intertank, AFT at LRB attachment ring
**Orientation:** To be optimized
**Force:** (TBD - Expected to be 100 - 200 Klb)
**Stroke:** (TBD - Expected to be 2 - 10 Ft)
**Action Time:** (TBD - Expected to be .2 - 1 sec)
**System Weight***: (TBD - Approx 2,000 Lbs)
**System Costs***:
**DDT&E:** (TBD) **Reccuring:** (TBD)

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**Qualitative Evaluation:**

**PRO:**

- Eliminates plume damage to Orbiter
- Simple, minimal avionics/control commands; no active control
- Fast response time

**CON:**

- Modifications to ET required: reinforce intertank center ring frame, modify forward stringers, add additional attachment fittings, strengthen LH2 tank major ring frame (total ET mods ~ 700 Lbs)**

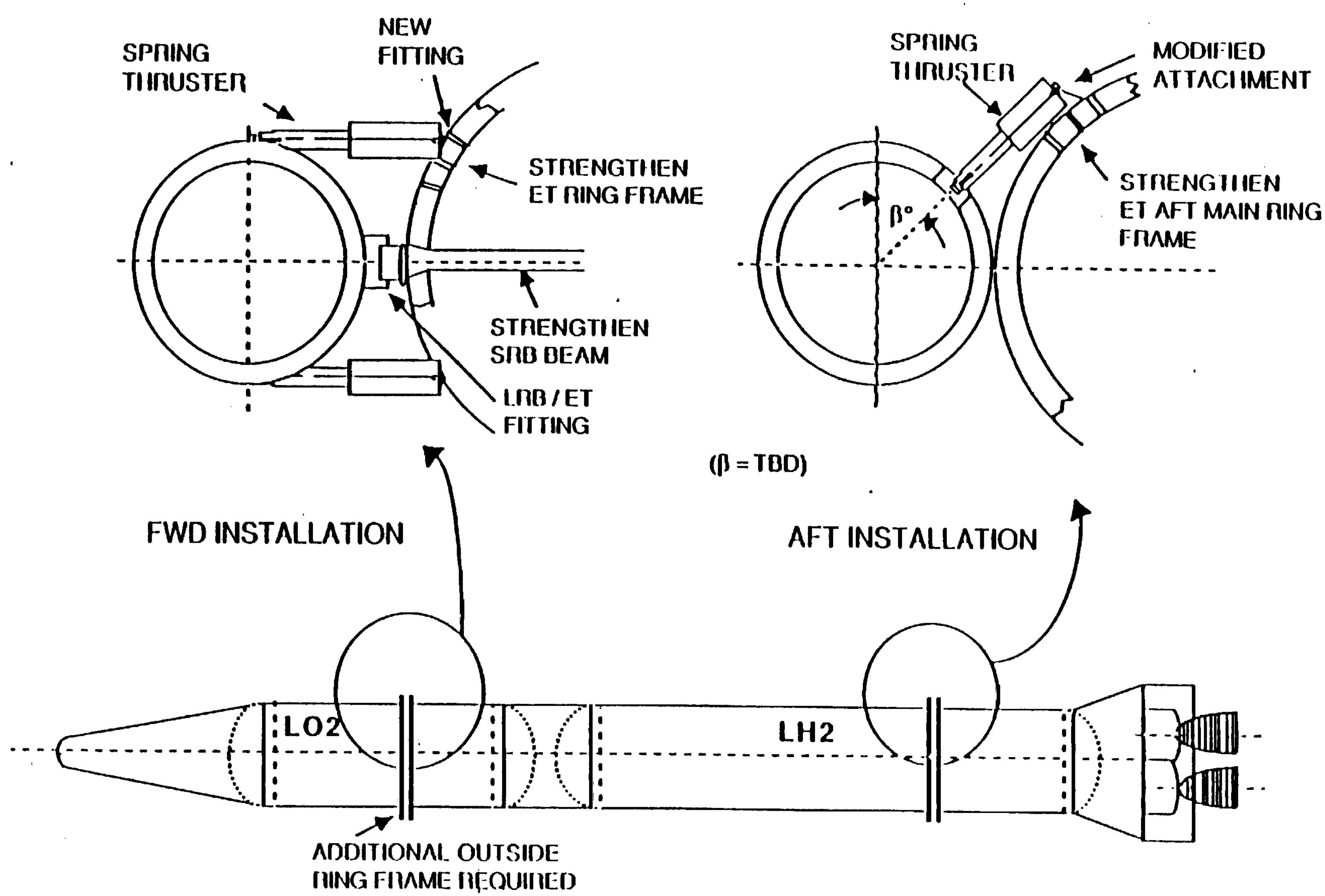
* For Normal Separation
** -kwell Estimate

## 2.1 Evaluation Con't

- Additional structure required on LRB: large intertank ring frame, additional intertank skin and stringer structure
- Large total system weight due to additional structure (on LRB & ET)
- Costs will be prohibitive if requalification of entire ET is required
- Redundancy requirements may dictate use of dual separation thrusters

# SEPARATION OPTIONS

## MECHANICAL SEPARATION SYSTEM (FWD & AFT SPRING THRUSTERS)



# Option Evaluation Sheet

**Option 2.1** (B) : Spring Thrusters (FWD Spring Thruster Located on LO2 tank)

**Description:**

**Location:** FWD on LO2 tank, AFT at LRB attachment ring
**Orientation:** To be optimized
**Force:** (TBD - Expected to be 100 - 200 Klb)
**Stroke:** (TBD - Expected to be 2 - 10 Ft)
**Action Time:** (TBD - Expected to be .2 - 1 sec)
**System Weight***: (TBD - Approx 2,000 Lbs)
**System Costs***:
DDT&E: (TBD) **Reccuring:** (TBD)

Note: If the LBR FWD attachment is not in the intertank, then two forward separation thrusters are required

**Qualitative Evaluation:**

PRO:

- Eliminates plume damage to Orbiter
- Simple, minimal avionics/control commands; no active control
- Fast response time

CON:

- Modifications to ET required: reinforce intertank center ring frame, modify forward stringers, add additional attachment fittings, strengthen aft LH2 tank major ring frame (total ET mods ~ 700 Lbs)**

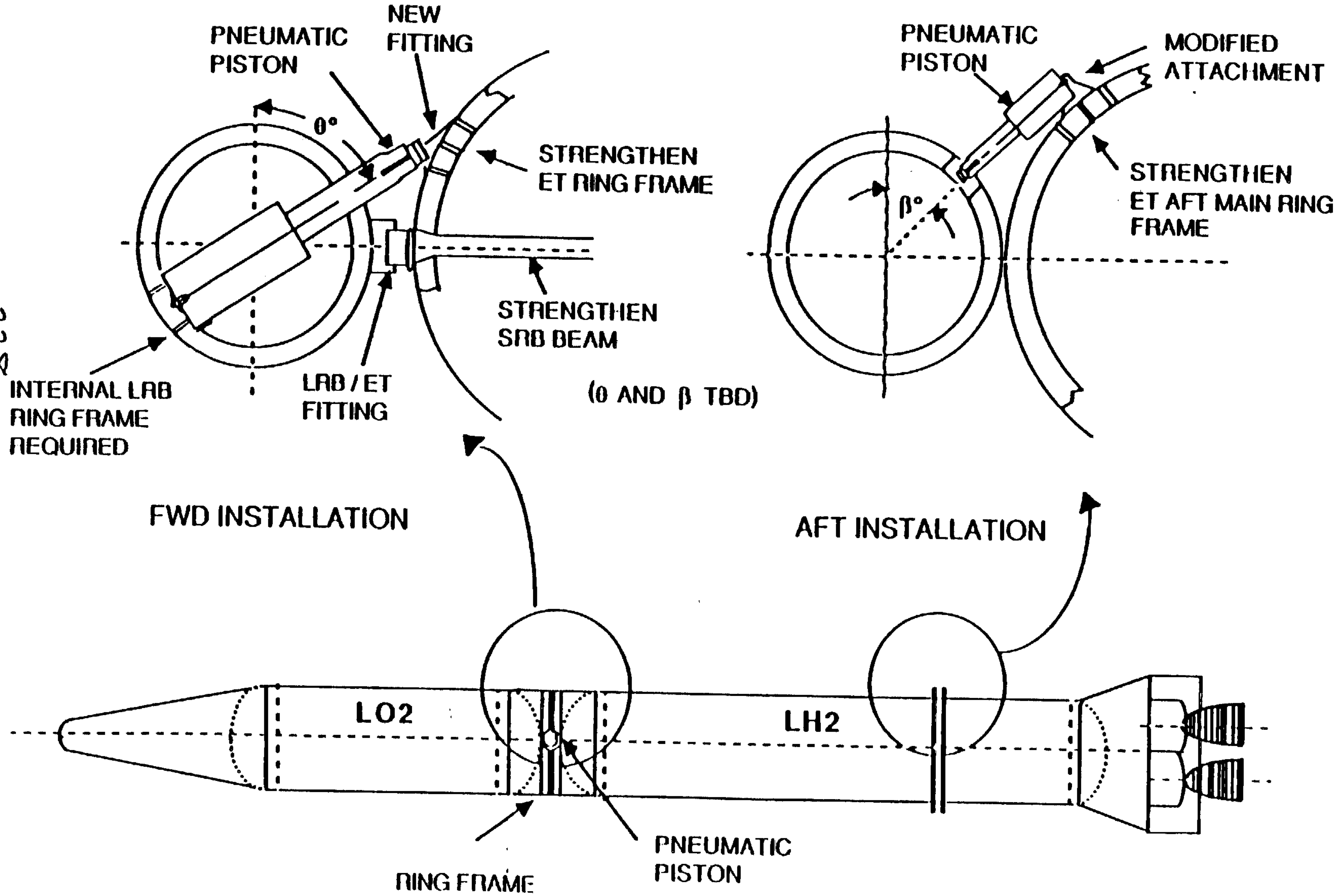
* For Normal Separation
**Rockwell Estimate

2.1 Evaluation Con't

- Additional structure required on LRB: external ring frame, additional tank stringer structure
- Large total system weight due to addition
- Costs will be prohibitive if requalification of entire ET is required
- Redundancy requirements may dictate use of dual separation thrusters

# SEPARATION OPTIONS

## MECHANICAL SEPARATION SYSTEM (FWD & AFT PNEUMATIC PISTONS)

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# Option Evaluation Sheet

**Option 2.2 (A) : Pneumatic (GHe or GN2) Pistons (FWD piston Located in Intertank)**

**Description:**

**Location:** FWD in intertank, AFT at LRB attachment ring
**Orientation:** To be optimized
**Force:** (TBD - Expected to be 100 - 200 Klb)
**Stroke:** (TBD - Expected to be 2 - 10 Ft)
**Action Time:** (TBD - Expected to be .2 - 1 sec)
**System Weight*:** (TBD - Approx 2,000 Lbs)
**System Costs*:**
**DDT&E:** (TBD) **Reccuring:** (TBD)

**Qualitative Evaluation:**

**PRO:**

- Eliminates plume damage to Orbiter
- Simple, minimal avionics/control commands; no active control
- Fast response time

**CON:**

- Modifications to ET required: reinforce intertank center ring frame, modify forward stringers, add additional attachment fittings, strengthen LH2 tank major ring frame (total ET mods ~ 700 Lbs)**

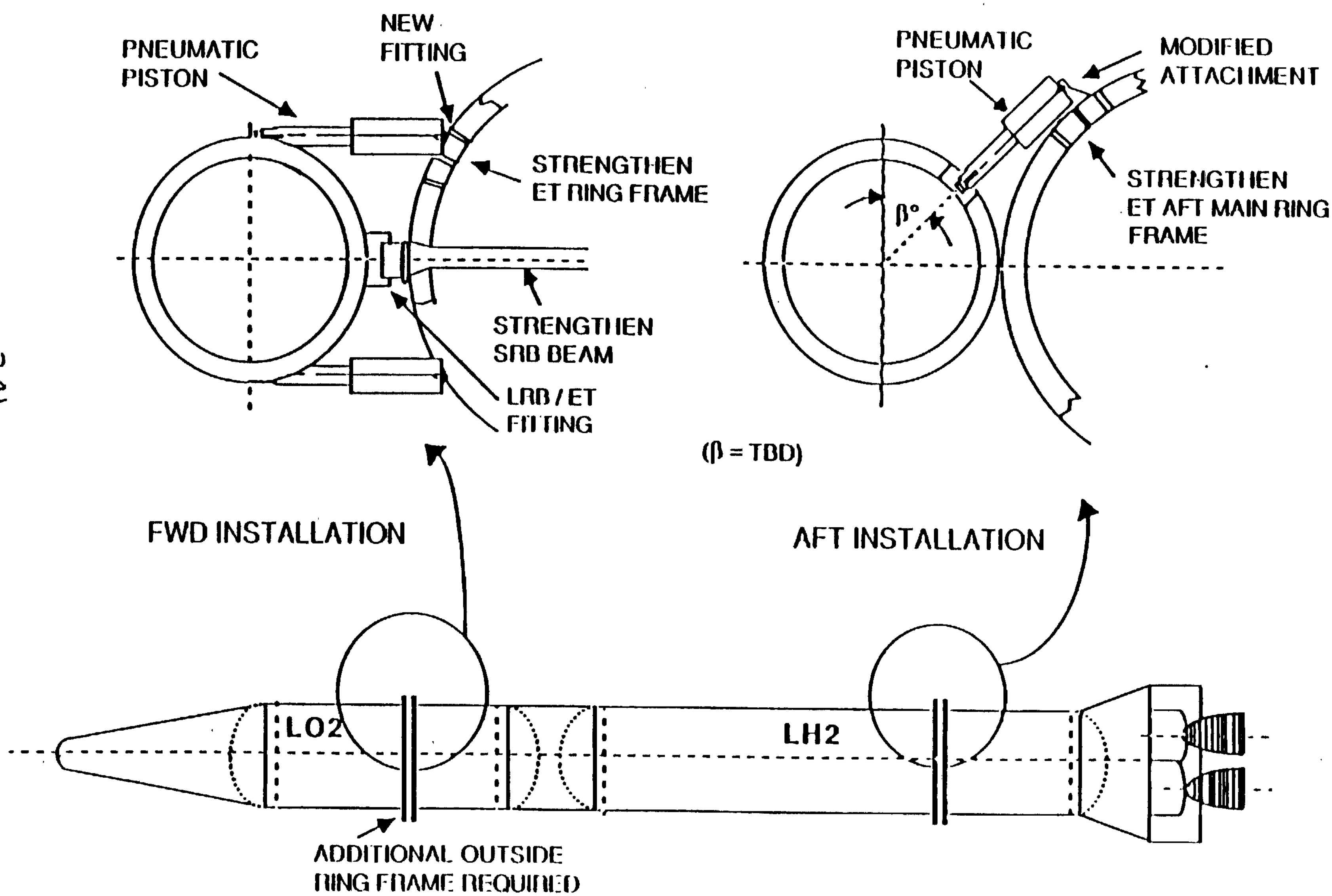
* F-r Normal Separation
ckwell Estimate

2.2 Evaluation Con't

- Additional structure required on LRB: large intertank ring frame, additional intertank skin and stringer structure
- Large total system weight due to additional structure (on LRB & ET)
- Costs will be prohibitive if requalification of entire ET is required
- Redundancy requirements may dictate use of dual separation pistons
- Lower reliability than spring thruster due to additional high pressure seals required

# SEPARATION OPTIONS

## MECHANICAL SEPARATION SYSTEM (FWD & AFT PNEUMATIC PISTONS)



# Option Evaluation Sheet

**Option 2.2 (B): Pneumatic (GHe or GN2) Pistons (FWD Piston Located on LO2 tank)**

**Description:**

**Location:** FWD on LO2 tank, AFT at LRB attachment ring
**Orientation:** To be optimized
**Force:** (TBD - Expected to be 100 - 200 Klb)
**Stroke:** (TBD - Expected to be 2 - 10 Ft)
**Action Time:** (TBD - Expected to be .2 - 1 sec)
**System Weight*:** (TBD - Approx 2,000 Lbs)
**System Costs*:**
DDT&E: (TBD) Reccuring: (TBD)



Note: If the LBR FWD attachment is not in the intertank, then two forward separation pistons are required

**Qualitative Evaluation:**

**PRO:**

- Eliminates plume damage to Orbiter
- Simple, minimal avionics/control commands; no active control
- Fast response time

**CON:**

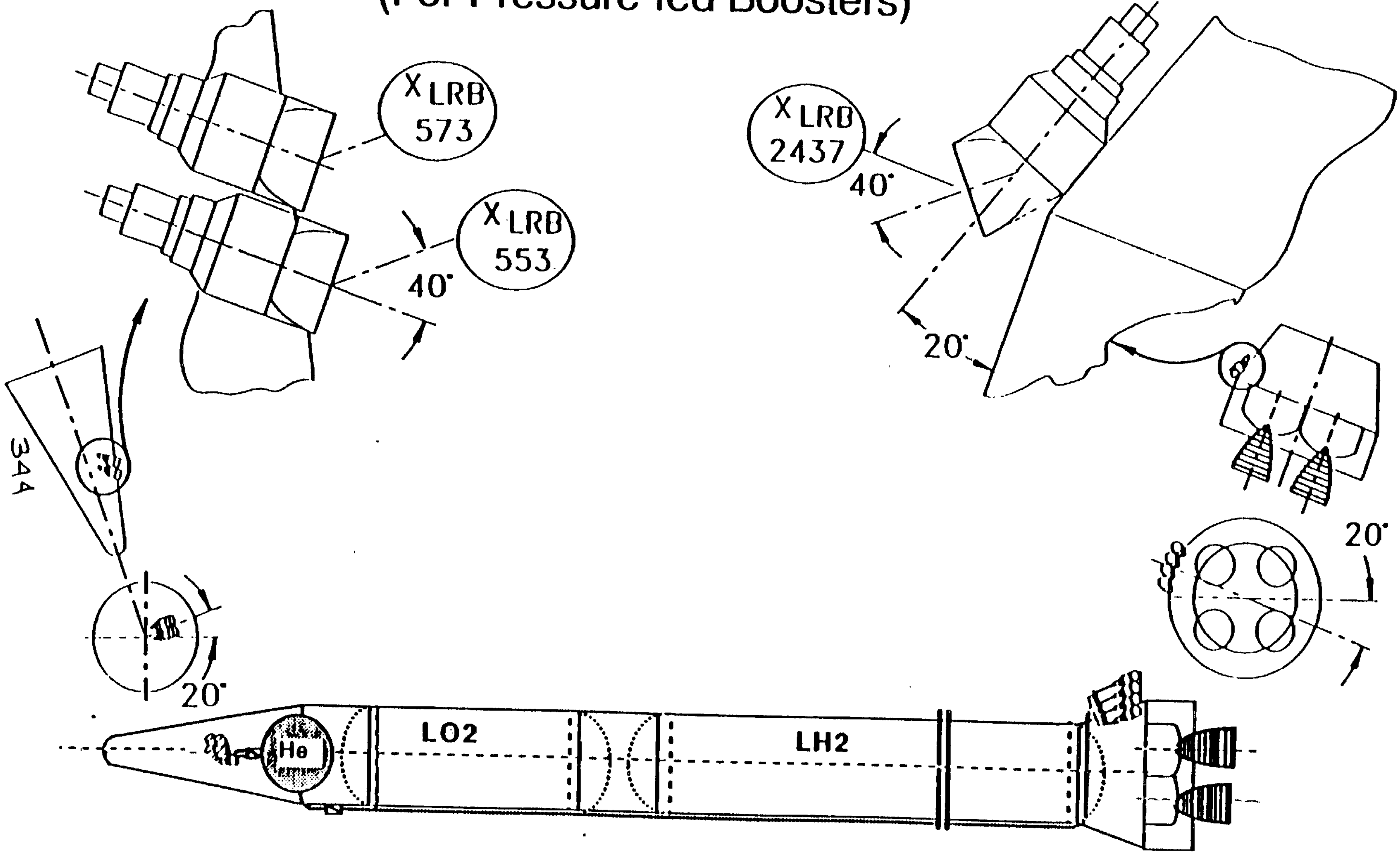
- Modifications to ET required: reinforce intertank center ring frame, modify forward stringers, add additional attachment fittings, strengthen aft LH2 tank major ring frame (total ET mods ~ 700 Lbs)**

* For Normal Separation
**Rockwell Estimate

2.2 (B) Evaluation Con't

- Additional structure required on LRB: external ring frame, additional tank stringer structure
- Large total system weight due to additional structure (LRB & ET)
- Costs will be prohibitive if requalification of entire ET is required
- Redundancy requirements may dictate use of dual separation pistons
- Lower reliability than spring thrusters due to additional high pressure seals

# TANK BLOWDOWN OPTION
## (For Pressure-fed Boosters)



# Option Evaluation Sheet

**Option 3.0** : Tank Blowdown (Helium Bleed to provide impulse) - Note: this separation system would be considered for a pressure-fed LRB only.

**Description:**

**Location:** Forward Frustrum & Aft Skirt (To Be Optimized)
**Orientation:** Current BSM orientation (To Be Optimized)
**Thrust:** (TBD - Expected to be 10-50 KLb) per nozzle
**Total Impulse:** (TBD) per nozzle
**System Weight***: (TBD)
**System Costs***:
**DDT&E:** (TBD) **Reccuring:** (TBD)

**Qualitative Evaluation:**

PRO:

- Moderately simple: No combustion required, but control valves and sensors needed
- Can vary thrust & durations
- Possible reusablity
- Eliminates plume damage to Orbiter
- Pressure in He tank(s) will be greater for abort (early) separation
- Fast response time

CON:

- Serious concerns about feasiblity to generate enough thrust/impulse
- Separation system intimately linked to main propulsion system; i.e.; He tank failure jeopardizes separation capability
- Heavier than NSTS BSM's
- Active control required and timing of operations may be critical

* - Normal Separation

# Option Evaluation Sheet

**Option 3.0** : **Tank Blowdown (Helium Bleed to provide impulse) - Note: this separation system would be considered for a pressure-fed LRB only.**

**Description:**

**Location:** Forward Frustrum & Aft Skirt (To Be Optimized)
**Orientation:** Current BSM orientation (To Be Optimized)
**Thrust:** (TBD - Expected to be 10-50 KLb) per nozzle
**Total Impulse:** (TBD) per nozzle
**System Weight***: (TBD)
**System Costs***:
**DDT&E:** (TBD) **Reccuring:** (TBD)

**Qualitative Evaluation:**



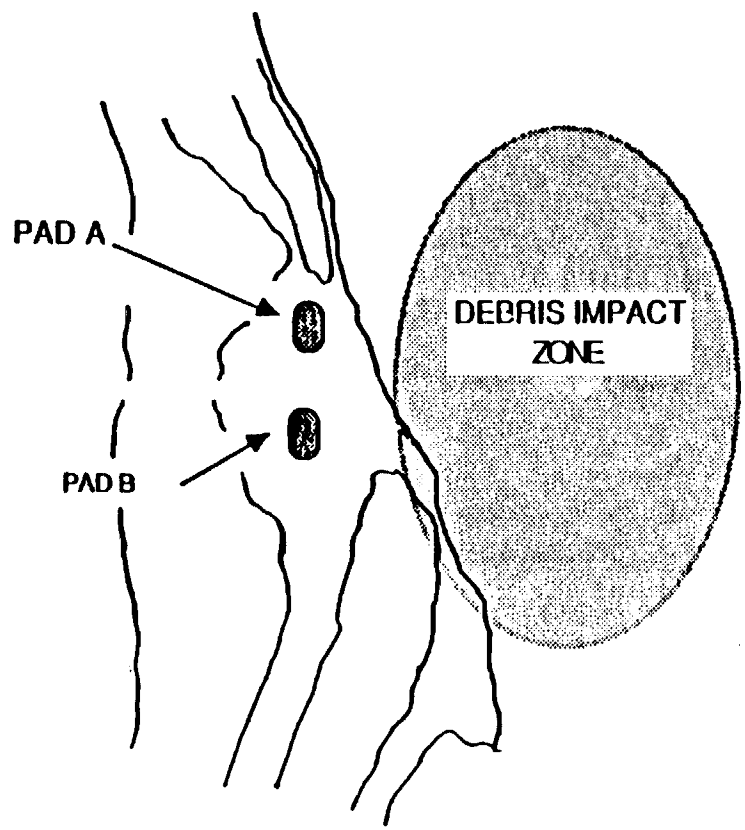
PRO:
- Moderately simple: No combustion required, but control valves and sensors needed
- Can vary thrust & durations
- Possible reusablity
- Eliminate plume damage to Orbiter
- Pressure in He tank(s) will be greater for abort (early) separation
- Fast response time

CON:
- Serious concerns about feasiblity to generate enough thrust/IMPULCE
- Separation system intimately linked to main propulsion system; i.e.; He tank failure jeopardizes separation capability
- Heavier than NSTS BSM's
- Active control required and timing of operations may be critical

* For Normal Separation

# TRADE STUDY 1.16 - SEPARATION SYSTEM SELECTION
## LRB Disposal After Separation

- Disposal Of LRBs Will Be An Important Issue If They Are To Be Recovered
- Impact Footprint Of Debris After Near Pad ( < 10 Miles Downrange)
  LRB Separation And Commanded Booster Destruct Need To Be Analyzed



LRB

GENERAL DYNAMICS
*Space Systems Division*

Date: March 1, 1988 GDSS-LRB-MIN-88-027

To: Distribution

From: Dan Heald

Subject: Minutes of an LRB Interim Engineering Review Board (ERB) for Separation System Selection (T.S. 1.16) conducted 26 February 1988.

Attachment: Trade Study ERB Viewgraph Charts

Purpose: This was an interim ERB for this Trade Study and was held to present the current results to provide information and obtain concurrence or redirections on this trade before the final review.

Discussion: ERB members present: Dan Heald - Chairman, Paul Brennan, Steve Seus, Ed Russ, Ron Koontz, Peter Stubner, Frank Hauser, Tina Nguyen, Scott Stumpf, Don Schnattschnieder, Guy Buchanan, and Carol Pouliot.

Paul Brennan, the Trade Study Leader, presented the preliminary results of the trade using the attached charts. Paul presented the key considerations for abort, including orbiter failures, LRB failures and response times. In reference to the Aero Data Comparison chart, it was suggested that the subtitle read "Aero Data Comparison for Nominal Separation." Paul Brennan received an action item to convert the coefficients to forces on the graphs of this page.

On the chart of Control Considerations, it was decided that the Maximum Pitch Gimbal and the Maximum Yaw Gimbal values were reasonable, but that for a conservative estimate one should analyze a flex body. It was suggested that Paul show nominal separation vs. early separation and that the method for doing the statistical correlation (root sum square) for determining the shut down thrust differential be added to the chart.

The Separation Cue and Sequence chart indicates that the cue will be based on a "low fuel level sensor." This should be discussed with Eagle Engineering. The question remains as to what will control separation for aborts: vehicle, ground control, or crew.

In discussing the preliminary sizing results, it was determined that early separation has a weight penalty of only about 2300 lbs. compared to normal separation. Need to discuss benefits of early separation with Walter Thompson. Range safety issues must be investigated. Action item for Paul Brennan to locate newest safety document.

Conclusion was to stop further work until Walter Thompson, et al, can establish the early LRB separation design conditions.

Prepared By: Carol J. Pouliot
Systems Engineering

Approved By: Dan Heald
D.A. Heald
Chief Engineer - LRB

# TRADE STUDY 1.17
# LRB STIFFNESS, STRENGTH, LOADS

Contents:

## 1.0 Introduction

Prior to holddown release the space shuttle engines are ignited sequentially and health monitored. The SSMEs rise to full thrust level in approximately 4 seconds and during this period the whole stack , due to asymmetry of configuration and eccentric SSME thrust load paths, is pushed over laterally responding dynamically with high lateral displacements and base bending moments while the space shuttle is still attached to the ground support equipment (GSE) and MLP. There are limits to which the ground support equipment can track the lateral excursions and the holddown system can sustain the base loads. From the studies performed with candidate LRBs, an LRB 16 ft or less in diameter ,designed purely on the basis of strength, responds dynamically to the SSME thrust buildup with greater amplitudes of displacements and loads . The options for the flexible LRBs are either to simply increase the stiffness which results in additional weight, or to decrease the SSME thrust rise rate which is accomplished by staggering the ignition of SSME engines. In this study the impact of SSME ignition staggering was studied in detail for LRB configurations for load and deflection relief.

The launch sequence with LRBs is considered to be very similar and qualitatively result in similar response. There are however some differences between LRB liftoff and SRB liftoff. LRBs have more engines which require health monitoring ,similar to SSME engines, before holddown release. As a result LRBs will be held on pad with T/W ratio considerably higher than SRBs before holddown bolts are released. Whether or not a slow release system is required depends upon the T/W ratio of stack at the time of release. Included in this trade study is the determination of maximum T/W ratio ,for LO2/LH2 pump LRB configuration, at which the explosive bolt release system could be used.

**Objective:**

Establish the structural stiffness requirements for LO2/LH2 Pump,LO2/RP1 pump and LO2/RP1 pressure fed Boosters. Determine minimum Stiffness that does not impact the current Ground support equipment and the SSME ignition sequence. Determine Loads and perform a preliminary design. Determine the maximum T/W ratio with the current explosive bolt release system.

**Ground Rules:**

- Maintain the current ignition sequence for SSME engines
- Maintain current load levels at the attach points
- Maintain twang level similar to current STS

**Assumptions:**

- Nominal Thrust Buildup Sequence
- Booster Stiffness Primarily dominated by the Tank stiffness

**Guidelines:**

- Minimum Impact to ET and Orbiter
- Minimum Impact to the GSE
- Minimize Release loads

## 2.0 GSE Interface - ET Umbilical

ET umbilical follows the STS stack deflections during pushover (SSME thrust buildup) and is the primary interface area of concern between the Space Shuttle Vehicle and the GSE (Ground Support Equipment). The objective in this study is to predict the deflections of the ET umbilical and establish the minimum booster stiffness required to maintain the umbilical excursions to within the current ICD limits imposed on the current GSE . The ET umbilical is currently designed to track approximately 20 inches during SSME thrust buildup and 17 inches during the rebound (Shutdown).

## 3.0 Stiffness Requirement

The space shuttle is an asymmetric launch vehicle.During liftoff it subjected to a large lateral component of SSME thrust causing high lateral excursions of the stack on pad prior to release. The magnitude of SSME thrust and its very sharp rise rate are both responsible for large amplitude of lateral displacements and bending loads in the LRBs. The LRB structure ,therefore, should satisfy two requirements; first that excursions of the STS stack remain within the current GSE tracking limits and secondly that the base bending moment at the release time does not exceed the current levels. Both these requirements are influenced by the SSME thrust rise rate and the stiffness of the LRB structure.

### 3.1 Stiffness vs Strength- Monocoque

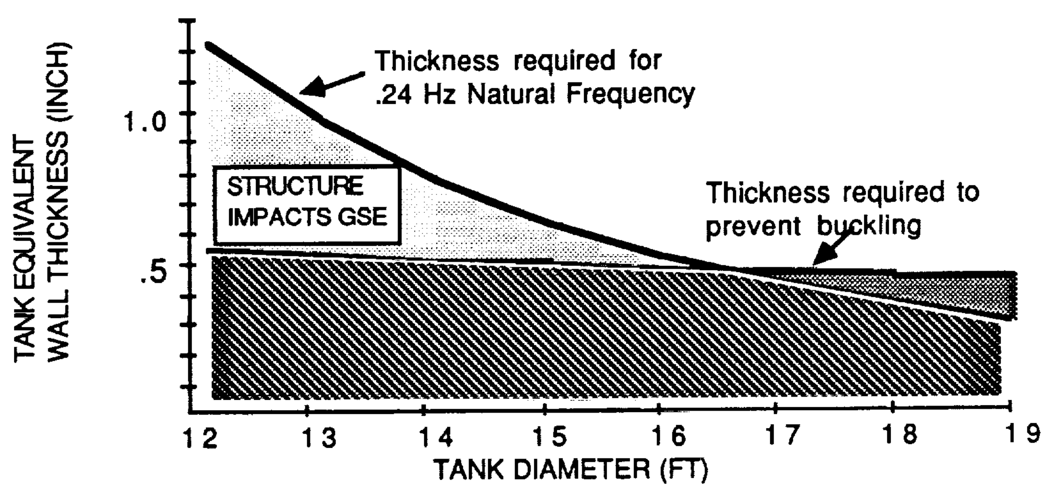
For LH2/LO2 boosters less than 16.5 ft diameter (approx.) the stiffness criterion governs the design and strength is automatically achieved. Lower diameter boosters designed for stiffness pay penalty in structural weight. This penalty is gradually reduced as the diameter is increased. Beyond 16.5 ft diameter the booster structure can be designed for strength. Figure 3.1-1 schematically illustrates stiffness and strength boundaries for various LRB diameters.

Monocoque tanks are designed to withstand loads up to onset of buckling of the cylindrical section.

Isogrid tanks are designed very similar to monocoque tanks- up to buckling load of the tank.

Skin Stringer tanks are designed to withstand applied loads until the buckling load of the stringer is reached. The skin between the stringers is allowed to buckle.

Figure 3.1-1 Stiffness vs Strength - Monocoque




Boosters less than 16.5 ft dia require stiffening
Lower the dia more the weight penalty

## 4.0 Options for Reducing ET Umbilical Deflections

There are two options to reduce the dynamic excursions of the stack:

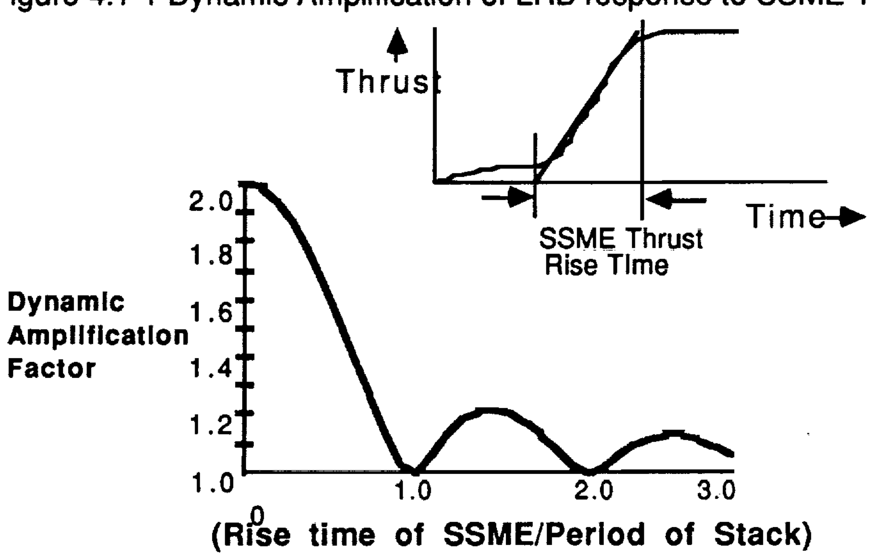
- Stagger the ignition of SSME engines
- Stiffen the structure

The dynamic amplitude of lateral excursions are a function of the ratio of the period of the structure and the thrust rise time of SSME engines.To maintain deflections witnin ICD limits, this ratio is this ratio ,in new designs, is maintained either by increasing the thrust rise time of SSME engines (staggering the start of SSME engines) or by stiffening the structure (reducing the period, increase frequency). Figure 4.1-1 shows the dynamic amplification factor against this ratio. The higher the ratio of periods, the lower the dynamic amplification factor and lower the amplitude of dynamic response.

LRB structure designed for strength and using SSME stagger to limit deflections are lighter in overall weight but impact the orbiter on board software. The bending loads at release are lower side and the twang is mild.

LRB structure designed for stiffness weigh more and may exceed the current base bending moment at the release. The twang may be more than current STS.

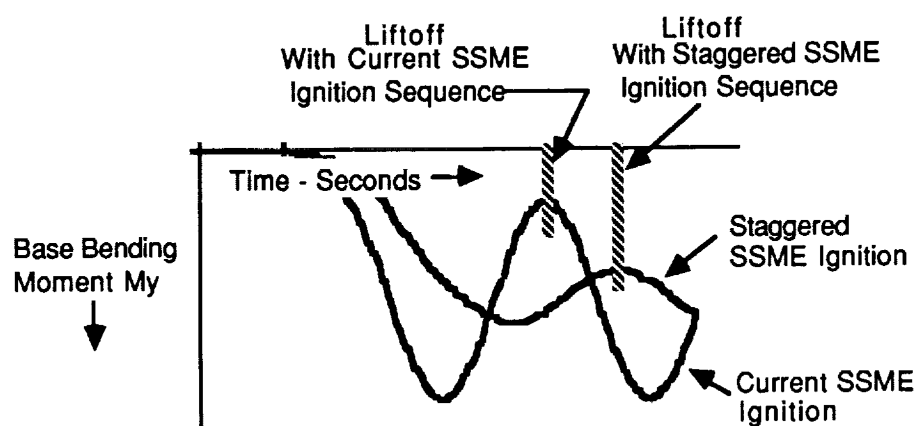
Figure 4.1-1 Dynamic Amplification of LRB response to SSME Thrust Rise



## 4.1 Option -1 Stagger SSME ignition sequence

The option to stagger the SSME ignition sequence is beneficial in reducing the maximum loads during pushover but delays the liftoff and also causes higher base bending moment at liftoff. Figure 4.1-2 schematically illustrates the consequences of staggering the ignition of SSME 2 and 3 engines. There is a trade-off between the maximum bending moment (or deflections), the bending moment at release, and the time to liftoff. The SSME fuel consumption may not be much affected as late ignition of SSME 2 and SSME 3 is compensated by the longer liftoff times. This option is, therefore, attractive if weight saving is very important. This is the case with lower diameter boosters which will require considerable increase in wall thickness to meet the stiffness requirements.

Figure 4.1-2 Influence of SSME Ignition Stagger on Loads




Base moment at holddown release (liftoff)
higher with stagger

Maximum base bending moment
lower with stagger

Liftoff is delayed with SSME stagger

BENIFITS

- Lower stresses in aft skirt better margin for safety
- lower ET umbilical excursions
- Lower structural weight

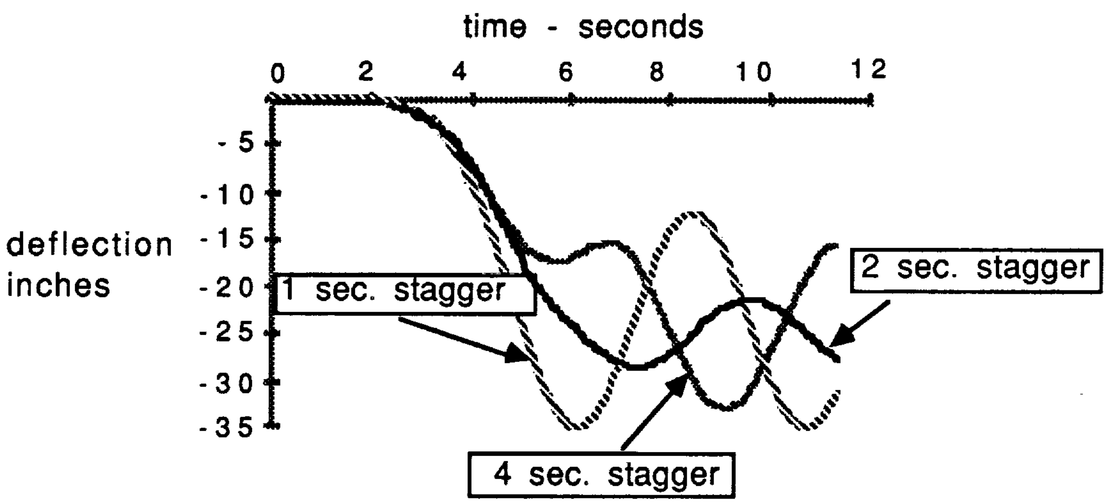
IMPACTS

- Change in GPC software only

#### 4.1.2 Optimal SSME Ignition Stagger

The optimal SSME ignition stagger is approximately equal to half the first fundamental period of the stack. If the start of SSME 2 and 3 engines is staggered by more than half the period then the displacement decreases in the first cycle of the displacement oscillation but builds up in the subsequent oscillations. Figure 4.1-3 illustrates the LO2/RP1 pump fed LRB response to stagger times of 1 seconds, 2 seconds, and 4 seconds and shows that for 2 seconds stagger , which is about half the period of the stack, the response is stabilized to a harmonic with lowest amplitide after 7 seconds. Normal liftoff takes place during first cycle of oscillation but FRF, which is a 20 second event, several oscillation cycles The stagger values higher than half the stack period are ineffective in limiting deflections during FRF and therefore are not recommended. The optimal stagger for RP1/LO2 booster is 2 seconds, at other values the deflections are higher during FRF.

Figure 4.1-3
Effect of stagger times on ET Umbilical Response
(LO2/RP1 pump)

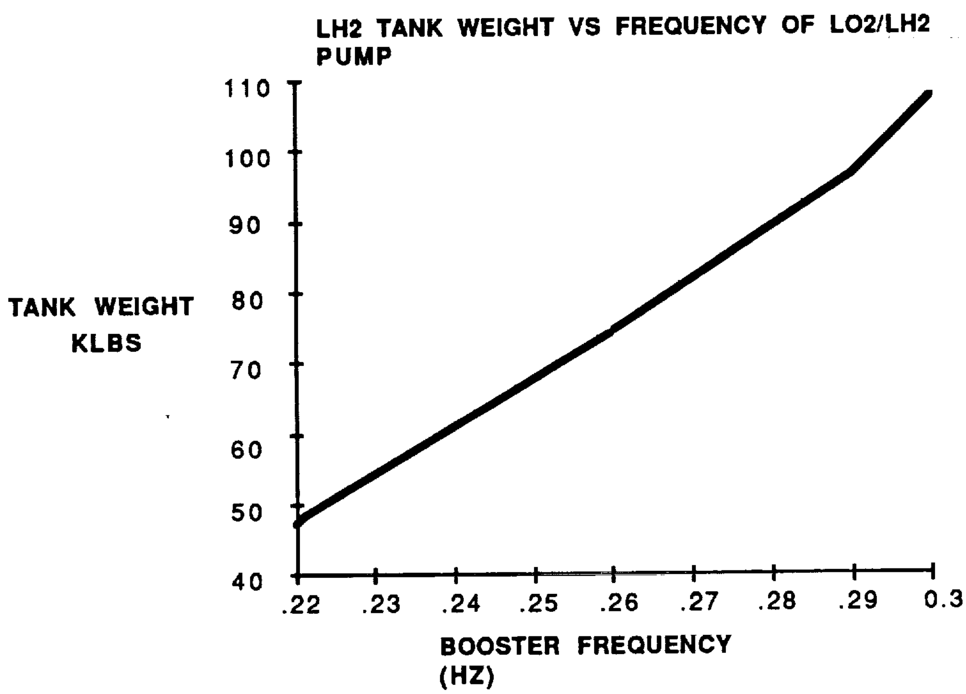


## 4.2 Option -2 Stiffen LRB Structure

Weight Impact

A monocoque construction with a first fundamental frequency of .2 Hz is 42000 lbs lighter than a monocoque construction (of same diameter) of the fundamental frequency of .3 Hz. This holds for LH2/LO2 pump fed booster approximately 15.8 ft diameter. Similar trends hold for other LRBs. Figure 4.2-1 Illustrates the impact of increasing the first fundamental frequency by maintaining the same diameter but increasing the wall thickness of the propellant and oxidizer tanks.

Figure 4.2-1 LH2 tank structural weight with first fundamental LRB frequency



## 5.0 Strength designed LRBs, SRB, FWC SRB and ASRM stiffness

The FWC motor case SRB which was to fly from Vandenberg Air Force Base had natural frequency of approximately .24 Hz. This booster was flight certified and was about to fly its intended mission. The deflection of ET umbilical is approximately 32 inches which exceeds the current specified ICD limit of 20 inches during buildup and 17 inches during rebound. ET umbilical modifications were performed to accommodate these deflections.

The ASRM (Advanced Solid Rocket Motor) request for proposal to the industry specifies ,in very specific terms , the minimum stiffness requirements for the new rocket motor case. The ASRM motor case stiffness is allowed to equal approximately to that of FWC motor case SRB. When ASRM is operational, the booster will weigh less, can be less stiff compared to current SRB, and consequently deflect more than current SRB.

The deflections of the strength designed LRBs and the current SRB are shown in the table 5.1-1. The LO2/RP1 pump fed booster is most flexible and deflects most. The LO2/RP1 pressure fed is most stiff and deflects less than SRB.

Extrapolation of our analyses results and the data on the current and previously designed boosters suggests a minimum frequency of .24 hz .At this stiffness level.the LRBs remain within the deflection envelope of Ground Support Equipment with the current liftoff sequence.

Table 5.1-1 ET Umbilical Deflections for Strength Designed LRBs and the SRB

| | SRB | RP1/LO2 PUMP | LH2/LO2 PUMP DIA 16.25 | LH2/LO2 PUMP DIA 18.0FT | RP1/LO2 PRESSURE |
|---|---|---|---|---|---|
| First Natural Frequency (HZ) | .31 | .21 | .22 | .29 | .28 |
| ET Umbilical Deflection (Inches) | | | | | |
| Current SSME Ignition sequence | 16.0 | 27.0 | 22.0 | 13.0 | 11.0 |
| With 2 seconds delay In SSME#2 and SSME#3 Ignition | | 22.0 | 16.0 | | 8.0 |

FLIGHT QUALIFIED FILAMENT WOUND CASE SRB DEFLECTED 30 INCHES

## 6.0 On pad Response of Strength Designed LRBs

### 6.1 LO2/LH2 Pump fed LRB

Two LO2/LH2 pump fed booster concepts, a 16.25 ft diameter and a 18.0 ft diameter ,were studied for the SSME thrust buildup and shutdown transient response.

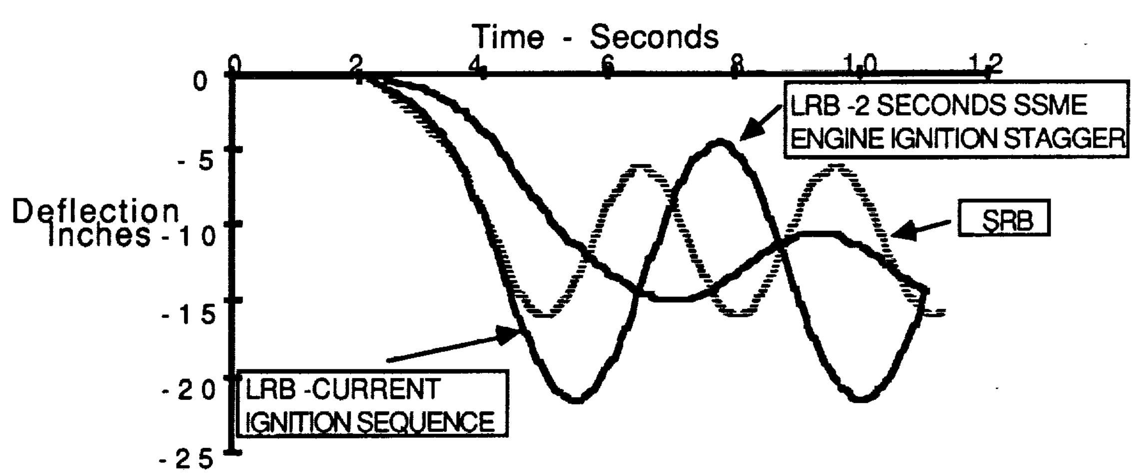
### 6.1.1 16.25 ft Diameter LO2/LH2 pump fed booster

SSME Thrust Buildup

The strength designed 16.25 ft diameter LO2/LH2 pump fed booster has a frequency of .22 Hz and its maximum ET Umbilical deflection with current SSME ignition sequence is approximately 27 inches. Figure 6.1-1 illustrates the SSME thrust buildup transient with current SSME ignition sequence, with 2 seconds delay in SSME 2 and SSME 3 ignition, and the corresponding SRB response. With the current SSME ignition sequence the deflection exceeds the current ICD limit on ET umbilical tracking capability and ,therefore, either the SSME ignition stagger or stiffening of the tank structure is required to satisfy the GSE constraints. If ET umbilical tracking capabilities are modified to track 27 inches then with the current SSME ignition sequence the liftoff takes place at 7.8 seconds. The Stack stays on the pad for approximately 1.1 seconds more than the current SRB system.

The deflections during SSME buildup are brought to SRB level by staggering the SSME engines; start engine 1 first and ignite SSME 2 and 3 engines simultaneously 2 seconds later. Although the deflection is approximately same as SRB deflection, the transient stretches and consequently the time to liftoff increases from 7.8 seconds (without stagger) to 9.4 seconds.

Figure 6.1-1 ET Umbilical Deflection during SSME Thrust Buildup
16.25 ft Diameter LO2/LH2 Pump LRB



SSME Shutdown The worst shutdown sequence for SSME 1 failure is if SSME 1 abort occurs at 16.6 seconds. Figure 6.1-2 illustrates the ET Umbilical displacement transient due to SSME 1 shutdown at 15.5, 16.6 seconds, 17.8 seconds, and 18.9 seconds. This covers engine shutdown during a time span equal to half period of the Stack. The response repeats in the interval equal to the period of the STS stack and therefore illustrates a situation during liftoff , at 4.6 seconds, 8.6 seconds, and during FRF which is a 20 second test event. For FRF the maximum response occurs when SSME 1 shutdown at 16.6 seconds. If the shutdown is due to an abort situation then, for a safe abort the SSME 2 and 3 are to be shutdown at 17.8 seconds and 18.9 seconds respectively. Figure 6.1-3 shows the combined response for this case. The maximum rebound due to this transient is 11 inches which is within the current GSE capability.

Figure 6.1-2 SSME 1 Shutdown Transient for ET Umbilical at various shutdown /abort times
16.25 Ft Dia., LO2/LH2 pump

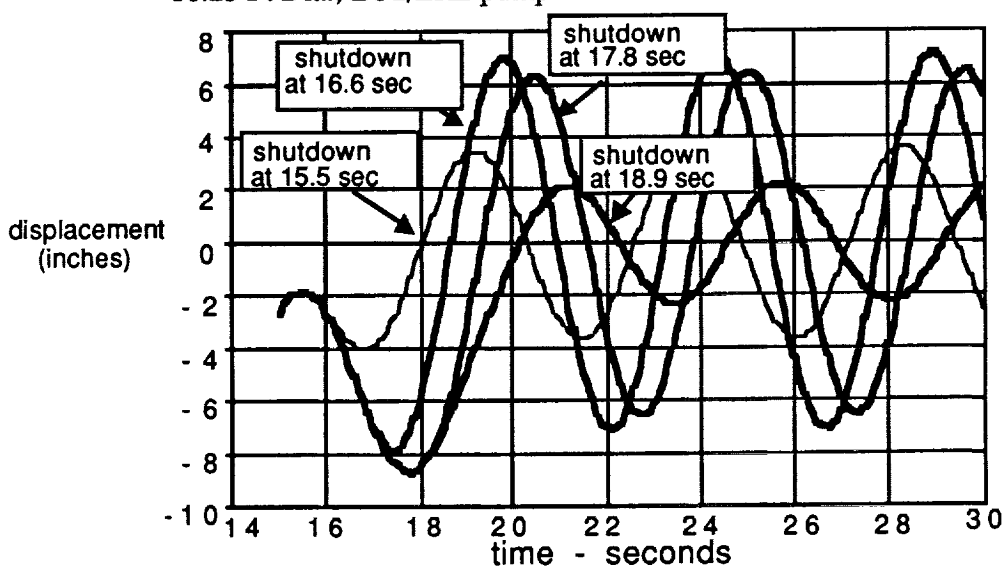
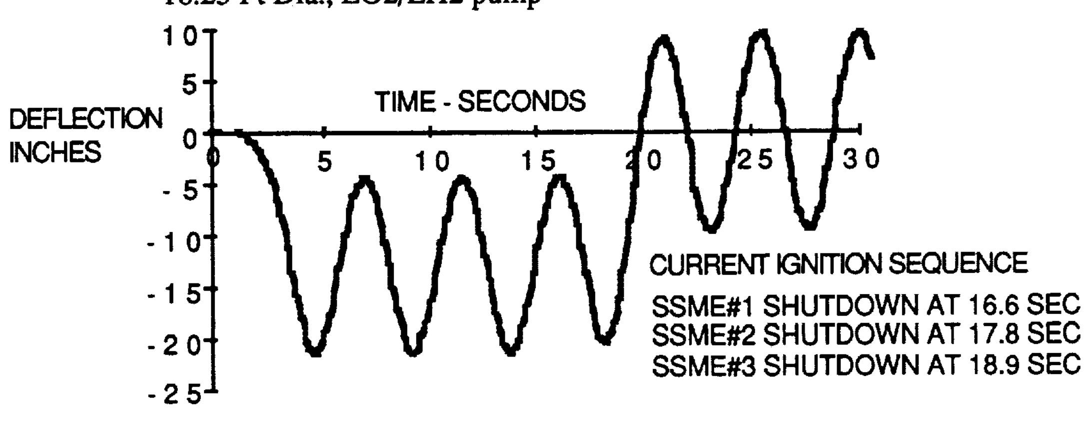


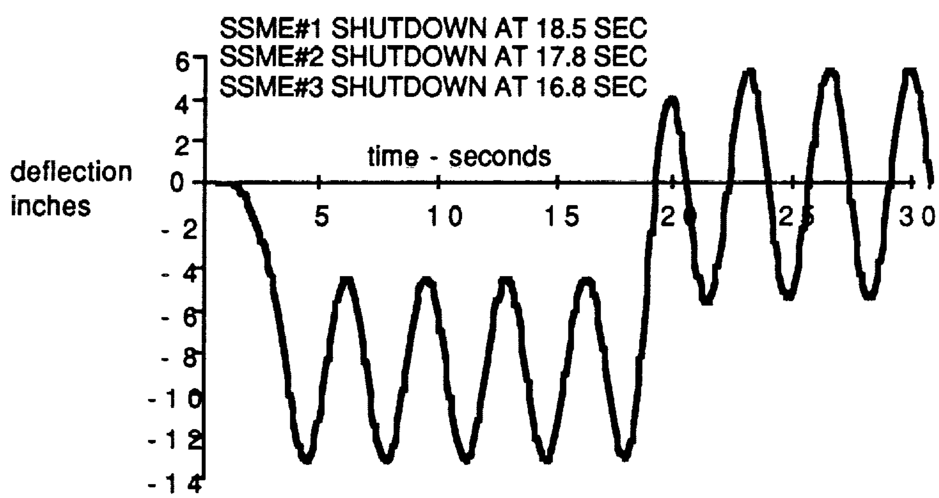

Figure 6.1-3 SSME Thrust Buildup and Shutdown Transient for ET Umbilical
16.25 Ft Dia., LO2/LH2 pump



### 6.1.2 18 ft Diameter LO2/LH2 pump

The buildup and shut down transient for a normal buildup and shutdown as in FRF is shown in the figure. The maximum deflections remain within the current GSE capabilities. There is no need to stagger the SSME engines or increase the stiffness. The optimal shutdown sequence is to shutdown SSME 3 at 16.8 seconds, SSME 2 at 17.8 seconds and SSME 1 at 18.8 seconds. Figure 6.1-4 shows the SSME thrust buildup and shutdown ET umbilical deflection response fo 18 ft diameter LO2/LH2 pump.

Figure 6.1-4 SSME Thrust Buildup and Shutdown Transient for ET Umbilical 18 Ft Dia., LO2/LH2 pump

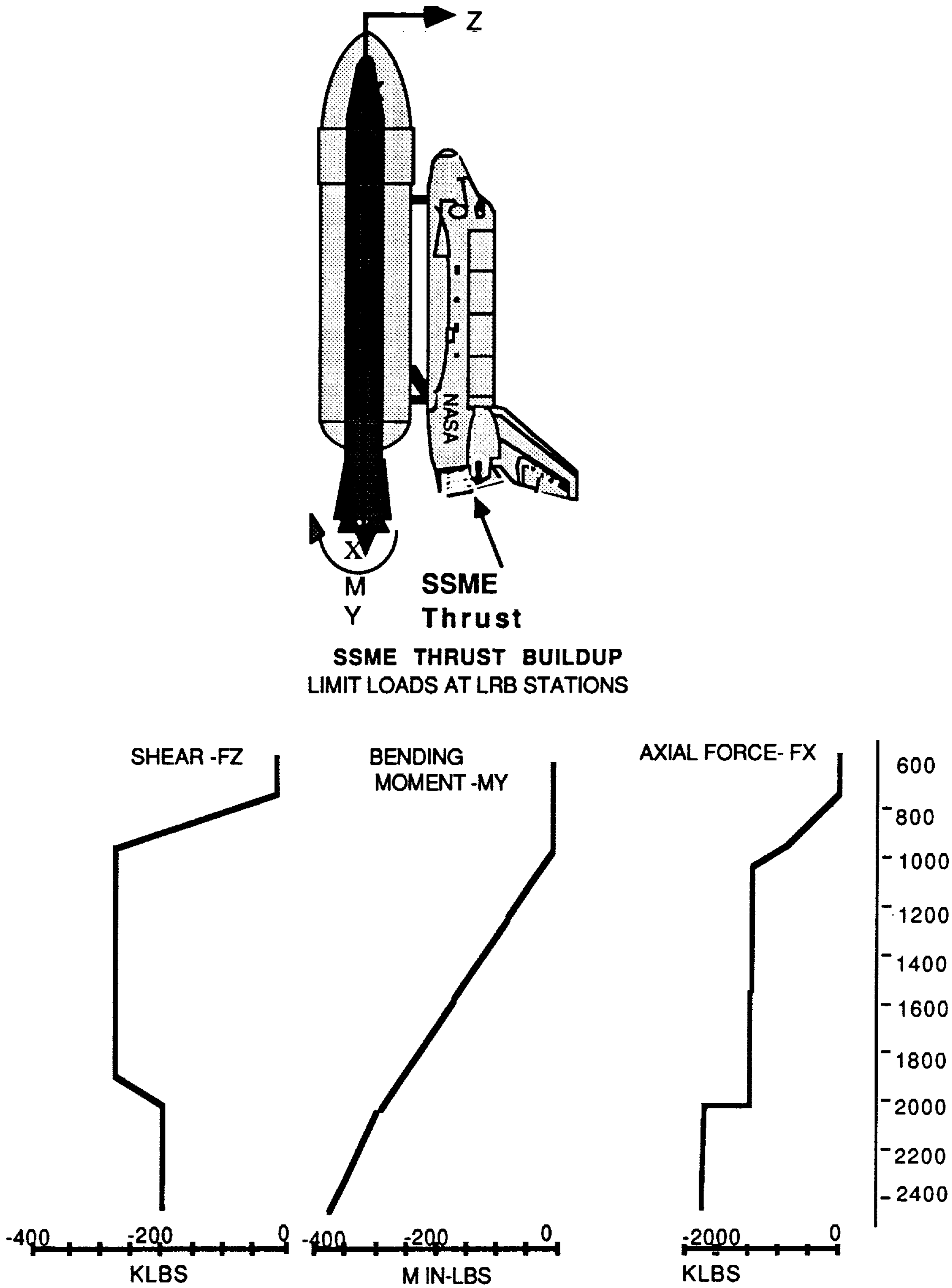


SSME Thrust Buildup loads

The lower segment of LRB experiences the maximum load during pushover. This condition is the design condition for overall design of LH2 tank. The bending moment at the base for LO2/LH2 boosters is slightly higher than the corresponding SRB values but poses no problem as the aft structure can be designed to accommodate these loads without impacting other Space Shuttle Components.

Shown in the figure 6.1-5 are the maximum design loads along the LRB length.

Figure 6.1-5 LO2/LH2 pump design loads- SSME thrust buildup



LH2 Tank Design

Based upon the derived loads and noting that the booster is more stiff than necessary two designs are developed. The first is the monocoque design in which the booster maintains slightly more stiffness and the skin stringer design which has lower stiffness than the monocoque.

The skin stringer design allows for limited skin buckling between the stringer and is therefore a weight efficient design. The monocoque is designed for stress levels below the the shell buckling limits. The skin stringer configuration for LH2 tank is shown in figure 6.1-6. Also shown in the figure is the thickness for a monocoque LH2 tank.

LH2 Tank Skin Stringer vs Monocoque

The skin stringer construction is lighter and more flexible than the monocoque. It experience higher dynamic base bending moments than the monocoque. Although its frequency is lower its deflections are maintained within the current GSE limits.

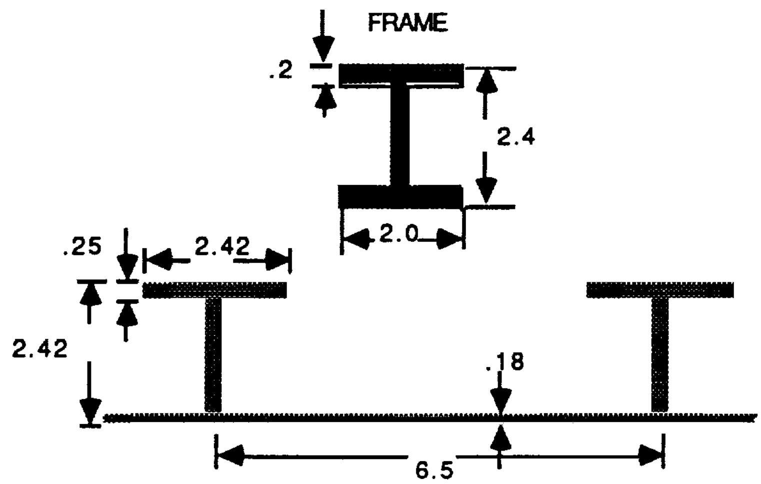
A monocoque tank is very stiff , has small on pad deflection, experiences lower dynamic base bending moment during pushover, is heavier,and responds with a higher base bending moment at the time of release (higher twang).

From all the considerations a skin stringer configuration for 18 ft diameter booster is an optimal design and is recommended.

Figure 6.1-6 LO2/LH2 pump LRB LH2 tank design based on current Loads 2219/T87 Al Alloy

SKIN- STRINGER DESIGN - INCLUDES CONSIDERATIONS FOR PLATE PROCUREMENT AND FABRICATION

104 STIFFNERS SPACED 6.5 INCHES APART
FRAMES EVERY 30 INCHES APART




MONOCOQUE DESIGN

WALL THICKNESS = .66 INCHES

## 6.2 LO2/RP1 Pump Fed LRB

The strength designed LO2/RP1 pump fed booster is the most flexible of all the designs. The booster deflection with current SSME ignition sequence is approximately 30 inches. Even with SSMEs staggered the deflection remains high. The dynamic response of this LRB is illustrated in figure 6.2-1. Staggering the SSME engines produces response to 22 inches which is still high.

The options to limit deflection are either stiffen the structure or stagger the SSME engines along with lowering gimbal angles of SSMEs or perform ET umbilical facility modifications. These Options are illustrated in figure 6.2-2.

The recommendation is to stiffen the structure up to .24 Hz natural frequency. From analyses this is the optimum level of stiffness with minimum weight penalty.

Figure 6.2-1 Influence of SSME ignition stagger on LO2/RP1 pump ET Umbilical Response

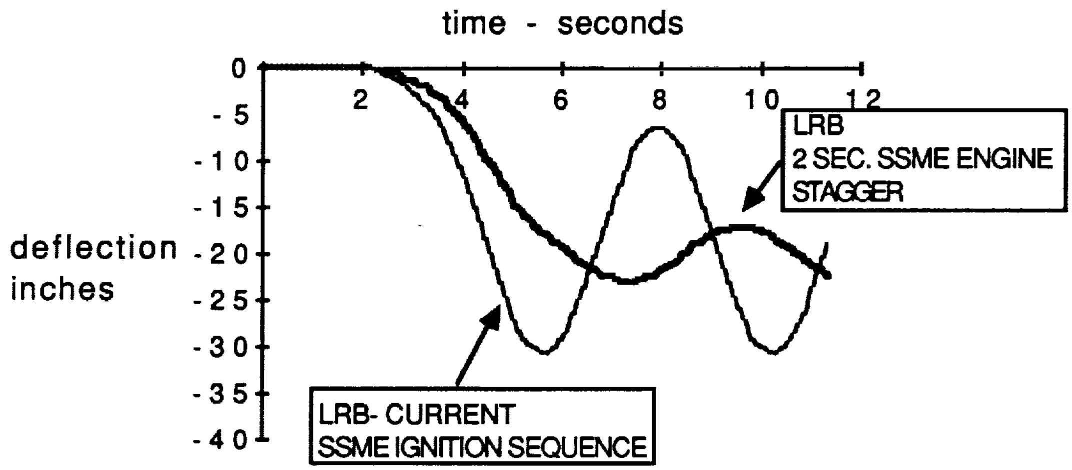
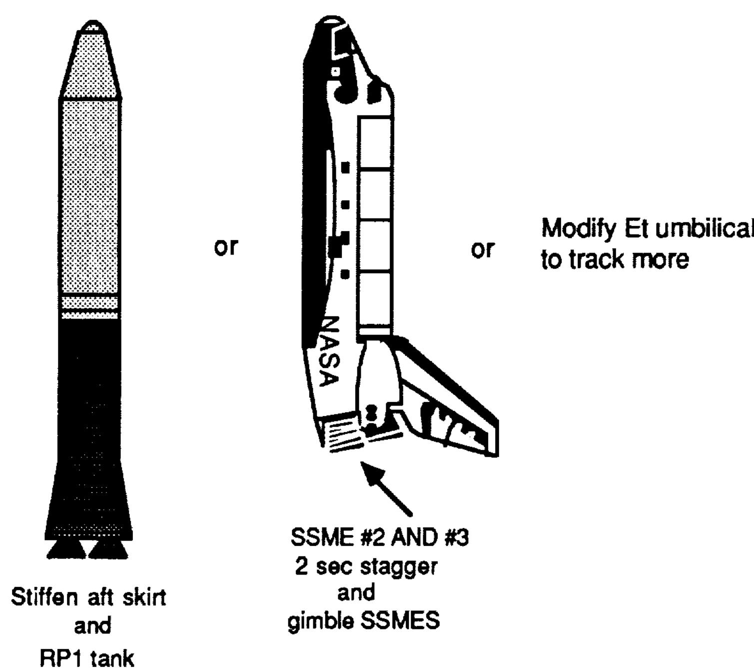



Figure 6.2-2 Options to lower the ET Umbilical Response



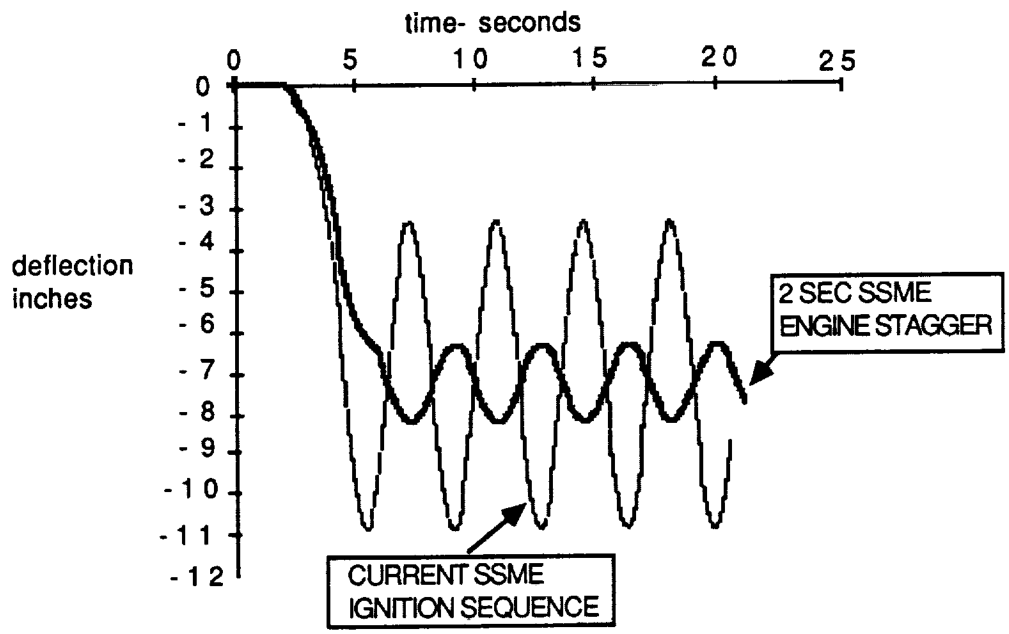

Recommend - stiffen to .24 hz and stagger SSMEs if required

### 6.3 LO2/RP1 Pressure Fed LRB

The LO2/RP1 pressure fed LRB is stiffer than the current SRB and therefore has no deflection problem. With stagger this booster has even smaller deflections. Figure 6.3-1 shows a typical pressure fed LO2/RP1 response.

Figure 6.3-1 SSME Thrust Buildup and Shutdown Transient for ET Umbilical

LO2/RP1 pressure



### 7.0 Maximum T/W Ratio for LO2/LH2 LRB Configurations At Release

LRB holddown and release requires all LRB engine health monitoring prior to holddown release somewhat similar to the way SSME s are currently monitored during launch. This engine health monitoring creates a new launch environment namely - liftoff at considerably high T/W ratio than the current STS with SRBs and results in a load transient at forward ET/LRB thrust fitting. An analytical study was performed to evaluate the forward attach fitting loads, generated from a sudden release (like the current explosive bolt release), for LO2/LO2 pump fed LRB configurations for different LRB thrust levels and thrust rise times. From this study the maximum LO2/LH2 pump LRB thrust on pad prior to release is established to be approximately 87% of the full LRB thrust level. The LO2/LH2 monocoque and LO2/LH2 skin stringer configurations both could be held on pad up to 87% of the full LRB thrust. The difference is in the time at which the forward attach fitting peaks.

The thrust fitting load transient for the monocoque is shown in figure 7.1-1 and the transient for the skin stringer configuration is shown in figure 7.1-2. The monocoque LO2/LH2 pump LRB achieves the limit load of 1634 KLBS at 1000 milliseconds while the skin stringer LRB achieves the limit at approximately 1400 milliseconds after holddown release. The current explosive bolt release system can be used if the LRB engine health monitoring can be performed below 87% of full LRB thrust level. Beyond 87% a slow release system is requited to damp the transient.

Figure 7.1-1
LO2/LH2 Monocoque Pump
Thrust Fitting Load Transient after Holddown Release
Holddown Relese at 87% of LRB Thrust Level

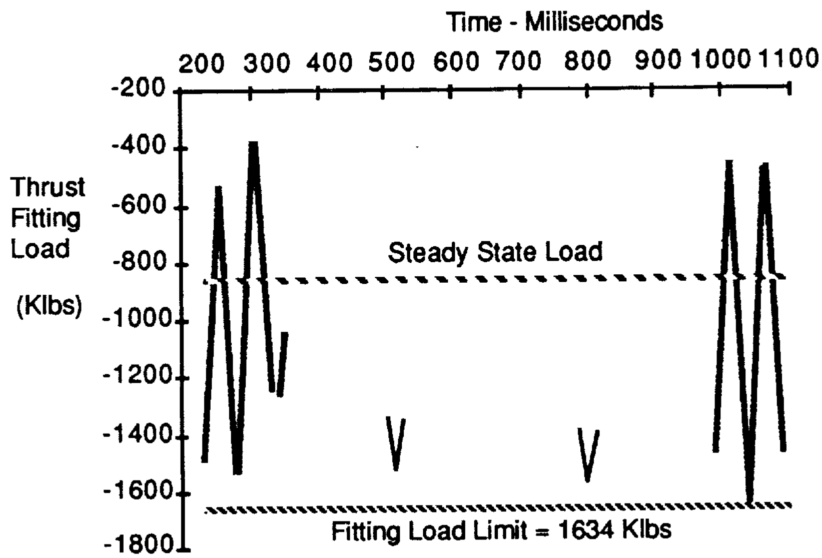
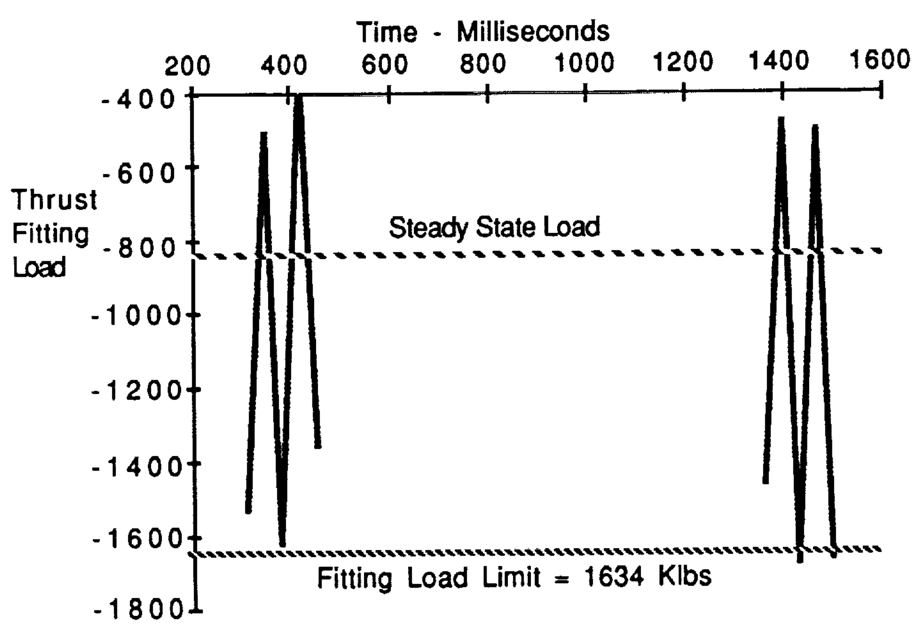



Figure 7.1-2
LO2/LH2 Pump -Skin Stringer
Thrust Fitting Load Transient after Holddown Release
Holddown Relese at 87% of LRB Thrust Level



## 8.0 Conclusions

The 18 ft diameter LO2/LH2 LRB monocoque or skin stringer designs are sufficiently stiff on pad and can be released using the current SSME ignition sequence. The current GSE equipment is capable of tracking the STS deflections during pushover. The quick release system (explosive bolt release) used currently with SRBs can be used for LO2/LH2 pump LRBs provided that the maximum LRB thrust at the time of release is less than 87%. The LRB engine health monitoring should be accomplished within 87% of full thrust level for LRBs. If the LRBs are released at higher than 87% of full LRB thrust level then a damped or slow release system is necessary to maintain thrust fitting loads to safe level.

The most flexible configuration is LO2/RP1 pump which either requires SSME ignition stagger and SRB structural stiffening to maintain deflections within the GSE capabilities. Limiting on pad deflections by increasing the structural stiffness only, while maintaining the diameter (13.7ft) results in considerable structural weight increase.

LO2/RP1 pressure fed booster is the most stiff configuration. The on pad deflections are well within the current GSE capabilities.